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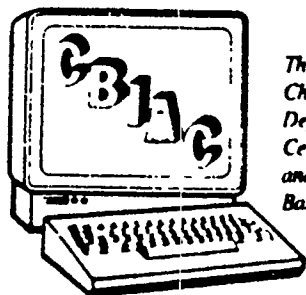
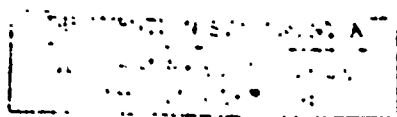
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Evaluation of a Lightweight Protective Mask Concept for Respiratory Protection Systems 21

To

U.S. Army Chemical Research,
Development and Engineering Center
Aberdeen Proving Ground, MD
21010-5423

JANUARY 1991



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**EVALUATION OF A LIGHTWEIGHT PROTECTIVE MASK
CONCEPT FOR RESPIRATORY PROTECTION SYSTEM 21**

to

**U.S. Army Chemical Research, Development,
and Engineering Center
Aberdeen Proving Ground, MD 21910-5423**

January 1992

by

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EVALUATION OF A LIGHTWEIGHT PROTECTIVE MASK CONCEPT FOR RESPIRATORY PROTECTION SYSTEM 21

1.0 INTRODUCTION

In the event of combat where Nuclear, Biological, or Chemical (NBC) weapons could be presented, the soldier must be protected while being able to perform his mission. NBC protective equipment for individuals included both protection for the body and the head. However, this equipment causes disadvantages due to the physiological burden on the soldier, such as:

- Reduction in vision, both field of view and acuity
- Degradation of communications, both speech and hearing capabilities
- Increased heat load by containing body heat and preventing exposure to cooling air

The U.S. Army Chemical, Research, Development, and Engineering Center (CRDEC) is entering development of the next generation of respiratory protection (RESPO 21) to replace the current M40 series of protective masks. One of the system concepts is a lightweight protective mask (LPM) which utilizes a barrier film for both the facepiece and hood. This concept provides a lightweight, conformal mask design which can be rolled or folded into a very small package. Concept studies have been completed for advanced seal designs, attachment systems, and electronics for this mask.

Battelle was contracted by CRDEC to integrate the results of the previous component studies and to evaluate methods for optimizing the functional characteristics of the LPM concept. This report documents the development process in designing and fabricating LPM prototypes.

2.0 OBJECTIVE

The objective of this program was to evaluate the feasibility of a lightweight protective mask concept for RESPO 21. This evaluation consisted of generating concepts and performing the fabrication and evaluation of prototypes.

3.0 TECHNICAL ACTIVITY

During the performance of the LPM development program, the following tasks were completed

- The design requirements for the LPM, the previous work on protective masks, and the on previous work components which could be used in the LPM concepts were reviewed
- New materials were researched which could be beneficial to the LPM design
- LPM concepts were generated
- Components and initial mask mockups were fabricated to further define the design
- The LPM prototypes were designed and fabricated
- Changes and improvements to the prototypes were identified which could be implemented in future prototype iterations.

3.1 Background Information

Background information on past mask developments, mask component design, and LPM requirements was obtained through discussions with CRDEC and reviewing information provided by CRDEC. The background information on the LPM development is presented in the following sections.

3.1.1 Design Requirement Identification

The design goals of the LPM were provided by CRDEC (ref 1,2,3) and include:

- Low weight and bulk
- Easily stowed
- Low profile design on the head while providing good comfort and fit
- Good optical properties while providing optical compatibility with existing sighting and weapon systems
- Low breathing resistance
- Provide chemical protection for 24 hours
- Withstand decontaminates

The current M40 protective mask system consists of a mask, a butyl-coated fabric hood, a filter canister, and a carrier for storing these components. This system weighs about 3.8 pounds and has a stowed volume of about 445 cubic inches (9 inches by 11 inches by 4.5 inches). The weight of the LPM system should be considerably less than the M40 mask system. Also, the LPM should be designed to roll or fold up allowing it to be carried in an existing pocket. To facilitate stowing the LPM, the filter assembly should be a flexible design and integral with the mask. This design approach will preclude mounting a heavy filter canister to the mask which would tend to pull the mask away from the face (i.e., break the face seal) while the soldier is running or handling other equipment. Another desirable design feature for both lightweight and low profile would be to make a single layer hood/facepiece which forms both the chemical barrier and the mask suspension.

The LPM mask design, especially the air management ducts and check valve assemblies, should have a low profile to minimize interference with other equipment, such as weapons during firing, sighting devices, helmets, etc. Of course, the LPM must form a good seal to providing high protection factors and minimize lens fogging when exhaling. In addition, the LPM should provide a comfortable fit to reduce the physiological burden on the soldier. The M40 mask is molded of silicone rubber for low temperature flexibility and comfort even though this material doesn't provide a good chemical agent barrier. Also, the M40 uses thick rubber straps and metal buckles to support the mask on the face. Because these straps and buckles cause pressure points, or "hot spots", this type of suspension should be replaced by an elastic design which uniformly distributes the pressure on the wearer's head.

The M40 mask lens system has an eye relief of 45 mm (1.77 inches) which greatly reduces the wearer's field of view and makes coupling with sighting devices and weapon systems difficult. For instance, the eye relief for most sighting devices is 25 mm (1.0 inch). To overcome the vision deficiencies of the M40, the LPM should have an optimum eye relief of 18 mm (0.71 inches) and should not exceed 25 mm (1.0 inch). The LPM lens system should also consist of a primary lens for chemical and ballistic protection, a laser protection outsert, and optical correction inserts. Both the laser protection outsert and the optical correction inserts should be field replaceable units without requiring special tools. The field of view (FOV) and the optical properties of the LPM lens system should be maximized. In addition, the various lenses should incorporate a two-lens system or a foldable design, thus eliminating the tendency of a single "windshield" design to break at the nose bridge.

The breathing resistance, both inhalation and exhalation, of the filter and the associated ducts and check valves should be minimized to reduce the physiological burden on the wearer. The flow resistance of the M40 filter canister is about 45 mm H₂O at 85 liters per minute (lpm) which doesn't include the resistance of the ducts and check valves. The goal of the LPM is to have a inhalation resistance of one half of the M40 mask. Provisions should also be made for including a 2-cubic-foot per minute (CFM) blower to the LPM for breathing assistance. The inhalation check valves and the nose/mouth seal should be designed to prevent fogging of the lenses in cold temperatures (which can be as low as -25°F) without breathing assistance.

The chemical barrier of the LPM should provide 24-hour protection to the wearer for all chemical agents. The barrier material should also not absorb the chemical agents which could then desorb at a later time to pose a chemical hazard. The LPM must not be degraded by exposure to other chemicals or fluid such as decontaminants, fuels, lubricants, etc.

The above requirements are the basic design goals of the LPM. The first concept drawing of the LPM, as provided in reference 1, is shown in Figure 1. Specific design goals of the LPM in quantitative terms are included in Appendix A.

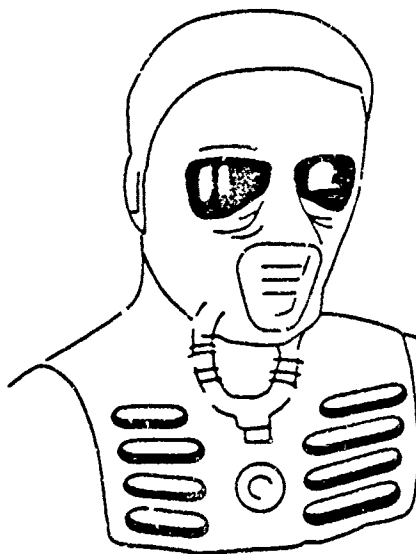


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FIGURE 1. LPM DESIGN FROM PATENT DISCLOSURE (REF 1)

3.1.2 Literature Review

Various reports were provided to Battelle by CRDEC on previous concept studies for the development of components and materials which could be used in the LPM concept. The descriptions of these reports are presented below. Additional reports, journal articles, and vendor catalogs were identified and reviewed during the development program; however, these references are introduced as their pertinent information is needed to describe the development process.

3.1.2.1 Chemical Barrier Materials

Several studies to identify chemical agent barrier materials have been previously completed and the reports provided to Battelle by CRDEC. The various materials investigated could be used in applications ranging from lens materials, lens hardcoatings, hoods, facepieces, and rigid check valve seats. Reference 4 was a study to identify materials which could be used in the following applications: elastomeric facepieces, flexible lenses, flexible optical coatings, rigid lenses, rigid components, and flexible barrier films for hoods. Reference 5 identifies and evaluates materials for four different applications: hardcoating for polycarbonate lenses; coated fabrics for use as hoods; "softshell" concepts of a facepiece seal, suspension, and nose cup; and transparent facepieces. Reference 6 lists the results of subjecting candidate materials identified in the above two studies to the chemical agent HD in the liquid form. Reference 7 details a study investigating possible flexible lens materials which could be used in the MCU-2/P mask. The original flexible lens material used in this mask was an aromatic urethane which was susceptible to long-term yellowing, suffered from significant blooming, would take a permanent set, and was degraded by DS-2 decontaminant. Summaries of these studies, along with some other sources, can be found in Appendix B relative to the application, material, material thickness, and time to breakthrough.

3.1.2.2 Lens Design

References 8, 9, 10, and 11 were provided by CRDEC describing several studies conducted to identify various lens geometries for different mask applications. Reference 8 presented general design guides for defining a lens system and proposed a number of concepts, including two-lens decentered designs, single-lens windshield designs, and two-lens designs based on the single-lens

windshield. The lens concepts were then evaluated relative to optical properties and producibility. Reference 9 describes the lens design for the XM40 single lens mask (SLM). This lens was to be compatible with combat spectacles, optical correction inserts, the SPH-4 helmet system, and night vision systems. Reference 10 identifies lens design specifications and guidelines to be used in RESPO 21 Individual Protection Equipment (IPE). This document specifies that the lens system must provide the capability of correcting vision from -9.00 diopters to +9.00 diopters for infantry. Reference 11 is an anthropometric survey report provided by CRDEC during the performance of this program. This survey of infantry troops found that the optical correction range of -7.00 diopters to +1.12 diopters covered 1 to 99 percentile of the survey population.

3.1.2.3 Other Literature

Reference 12 is a compilation of previous study summations provided by CRDEC relative to face and neck seal design, previous lens designs, voicemitters, voice amplifiers, respiratory design efforts, and cooling systems.

3.2 Chemical Barrier Materials

The materials forming the LPM barrier to chemical agent permeation must meet a number of functional requirements, such as:

- The material must resist permeation of the chemical agents for 24 hours
- The material must not absorb chemical agents allowing desorption of the chemical agent after the threat has been removed. Therefore, the material must not absorb the chemical agents, or if it does, it must be readily decontaminable or safely discarded.
- The physical properties of the material must not be degraded when exposed to the chemical agents or other chemicals common to the battlefield, such as fuels (e.g., gasoline, diesel fuel, JP-4), hydraulic fluids, and decontaminants (e.g., DS-2 and STB).
- The material must be lightweight.
- The material must be flexible (i.e., not board-like) so that it conforms to the wearer and is foldable.

- The material should not generate noise, such as swishing, when the wearer moves.
- The material must have sufficient strength, tear resistance, puncture resistance, and durability for use by a combat soldier. In addition, the material properties must not be degraded by environmental conditions, such as low or high temperatures, ultraviolet radiation, ozone, humidity, abrasion, etc.

Chemical permeation is a concentration-dependent phenomenon; the breakthrough time and steady-state permeation rate should vary with concentration.(ref 13) Chemical permeation relative to breakthrough time is defined by the time it takes for the chemical to go through the following three steps:

- Adsorption of the chemical through the outer material surface
- Diffusion through the material
- Desorption from the inner material surface.

Besides the breakthrough time, the permeation rate is also important because it determines the time from initial chemical breakthrough to the time that the exposure to the wearer reaches hazardous levels.

Breakthrough time has been found to be inversely proportional with the chemical concentration (ref 13) and to material thickness. During a study on glove thickness and chemical permeation (ref 14), it was found that material thickness is more likely to affect permanent breakthrough time (BT) than steady-state permeation rate (SSPR), though permeation rate did vary inversely with thickness for half of the systems they examined. A conclusion of this study is that the square root of the breakthrough time appears to be related linearly to thickness (i.e., doubling the thickness could increase the breakthrough time by a factor of 2^2 or 4). Therefore, it should be possible to predict a material thickness which offers a desired level of protection based on characterization of two or three test films of different thicknesses. Also, an inverse linear relationship between the glove material thickness and steady-state permeation rate was observed for the three glove systems tested. Therefore, a greater material thickness not only results in longer breakthrough times but should also reduce the degree of exposure. Caution should be exercised in using these

results because they are based on only a couple of single layer materials and solvent systems; the permeation of any given chemical through any given material and material thickness will be unique. However, these results can be used in a general sense which must be backed up with specific testing.

Since the permeation of chemical agents through a single-layer material is fairly complex, it can be very difficult to estimate the chemical permeation through a multi-layer material. As the permanent diffuses through the first material matrix, it must pass through the first and second material interface, followed by diffusion through the second material matrix, and so on until it desorbs from the inner surface of the last material layer. Multi-layer materials can be constructed using a material layer having very good permeation resistance with a layer which doesn't have good permeation resistance. Since the second layer is exposed to much lower permanent concentrations than if used alone, the permeation rate can be much lower. Also, if the first layer absorbs liquid chemical in a manner which induces the chemical to spread, the resulting concentration of chemical at the second layer interface is much lower than if the second layer alone is exposed to the chemical.(ref 15) The multi-layer approach can be implemented by placing a thin film barrier on top of a supporting layer. If a suitable barrier material is designed by increasing the matrix thickness or by incorporating multiple layers, the ability to decontaminate the material could also be reduced. Therefore, it is beneficial to place a barrier material near the surface exposed to chemical agents to minimize the amount of agents. The multi-layer approach can be implemented by placing a chemical barrier layer on the outer surface and a material layer on the inner surface which is comfortable to the wearer. An additional thin layer can be placed on the outer surface of the chemical barrier for additional environmental protection if required. Also, an intermediate layer can be placed between the chemical barrier layer and the innermost layer to facilitate bonding between the two primary layers or to provide a transition between the flexural characteristics of the two primary layers.

Almost as important as the material's ability to resist chemical agent permeation is its ability to be bonded to itself and to other materials without nullifying the barrier properties. For instance, if the material has to be sewn together, the needle holes have to be sealed, possibly with a sealing tape based on heat bonding or adhesive bonding. The manufacturing process or bonding process should not produce pin holes. Heat sealed seams or thermoforming must not cause significant thinning of the barrier material or degrade the barrier properties. Therefore, not only should the material itself be tested for permeation, but the fabrication interfaces should also be tested.

Along with the material literature provided by CRDEC were numerous samples of candidate materials. A large number of these samples were included in the chemical agent testing study of reference 6. The results of the material testing is presented in Appendix B. Because these tests were generally run as screening tests and not to find 24-hour barrier materials, promising barrier candidates should be further investigated. For instance, Fluorel® (a fluoroelastomer by 3M) is shown to provide 450+ minutes for HD and 400 minutes for GB when tested as a 2.5-mil thick sample coated on a slab of silicone (ref 4). When tested as a 75-mil thick sample, it provided 480+ minutes to breakthrough for both HD and GB.(ref D) Further testing is required to better define the permeation resistance. The 75-mil thick sample data doesn't provide much knowledge on permeation resistance since the test was stopped before the data points could be obtained. As discussed above, doubling the material thickness could possibly double or quadruple the breakthrough time. These tests results cannot be used to establish this type of relation between permeation and material thickness. Conducting thorough testing of the good candidates should include several material thickness data points relative to breakthrough time and complete documentation of the test and test sample. This detailed information will be invaluable for future protective clothing developers, since the material thickness can be optimized. For instance, a Fluorel® hood having a thickness of 5 mils might provide good stretch properties while increasing the breakthrough time by a factor of 2 or 4 (if a square relation). The minimum material thickness can be selected to provide desired strength, stretchiness, and barrier properties. This example is only presented to show the benefits of detailed data and not based on the physical properties of Fluorel® or to imply that 5-mil thick Fluorel could meet the LPM hood requirements.

In the LPM, chemical barriers are needed for the facepiece, hood, lenses, and any materials passing through the hood/facepiece, such as an exhaust check valve holder and lens holder. A materials search was conducted, based on the literature and materials provided by CRDEC and other sources, to identify materials for prototyping these components.

3.2.1 Impermeable Materials

A number of impermeable materials were identified where both chemical agent liquid and vapor penetration is resisted. The impermeable materials include coated fabric, non-fabric films, elastomeric materials, and other coatings.

3.2.1.1 Coated-Fabric Materials

A fluoropolymer and Nomex® laminate was identified which is presently being produced by Chemical Fabrics Corporation.(ref 13) This fluoropolymer coating is proprietary and is believed to be a PTFE (e.g., Teflon®). Challenger 5200, a fluoropolymer/Nomex® laminate also produced by Chemical Fabrics Corp., was previously tested for chemical agent permeation of HD by CRDEC.(ref 6) This material provided a breakthrough time of 432 minutes and was determined too stiff for a conformal hood design by CRDEC. Chemfab New York, the division which markets the fabric laminates, was contacted for newly developed materials which might be applicable to the LPM hood or facepiece. The following information regarding these materials (except for opinions of durability and drapability) was provided by Chemfab.(ref 16)

Chemical Fabrics Corp. does manufacture some basic chemical barrier materials. Material samples were provided to Battelle, including:

Chemlan X-22	Kevlar® with fluoropolymer on both sides. The material is stiff, but seems durable. Both sides are gray in color.
Challenge 4000	Nomex® with fluoropolymer on one side. The material seems fairly drapable. The coated side is orange in color and the uncoated side white in color.
Challenge 5000	Nomex® with fluoropolymer on both sides. The material seems not as drapable than the Challenge 4000, but seems more durable than the latter material. One coated side is orange in color and the other coated side tan in color.
MD-3	Fiberglass with fluoropolymer on both sides. The material seems fairly drapable and durable. The material is noisy when crumpled.
CPI-3	Fiberglass with fluoropolymer on both sides, heavier fiberglass (i.e., ounces per square yard) than MD-3. The material seems more durable than the MD-3, but not as drapable as the latter. Both sides of the material are black in color and it also generates noise when crumpled.

The standard laminates of Kevlar®, Nomex®, and fiberglass are either flame resistant or self-extinguishing. The fiberglass laminates are fracture sensitive since the glass fibers are relatively brittle. If the fiberglass laminate is folded over into a tight crease, the fibers will fracture and the laminate will easily tear. Also once a tear is initiated, tension perpendicular to the tear easily propagates the tear.

Originally, Chemical Fabrics Corp. could only coat the fluoropolymer on fabrics, such as Kevlar®, Nomex®, and fiberglass, which could withstand high temperatures. Only recently have they started to place fluoropolymer on low temperature fabrics, such as nylon and polyester. Some coated materials currently under development by Chemical Fabrics Corp. were supplied to Battelle, including.

STR 080691 N Nylon with fluoropolymer on one side. The nylon is about 3 oz/yd² and the fluoropolymer has a thickness of about 1 mil. The material seems somewhat drapable and durable. The coated side has a shiny green color and a dull light green color on the nylon side. This material does not seem to produce as much noise when crumpled as the fiberglass laminates.

STR 070191 A Nylon with fluoropolymer on both sides. This material is not as drapable as the nylon with fluoropolymer on only one side, but it seems more durable than the latter. Both sides of the material are shiny green in color.

STR 090591-D Polyester with fluoropolymer on one side. This material seems more drapable than the nylon coated with fluoropolymer on one side, but not as durable as the latter. The coated side is shiny green in color while the non-fluoropolymer side is light green in color. Noise is generated as the material is crumpled.

STR 090591-C Polyester with fluoropolymer on both sides. This material seems less drapable than the polyester coated with fluoropolymer on one side, but more durable than the latter. Both sides are shiny green in color. Noise is generated as the material is crumpled.

Chemfab provided chemical agent test data for HD to Battelle for the nylon and fluoropolymer laminates (ref 16). This liquid agent contamination/vapor penetration (LAC/VP) testing was reportedly performed in accordance with CRDECSP-64010. The nylon with fluoropolymer on one side (STR0 70181B) had HD exposed to the nylon side and resulted in a breakthrough time of about 20 hours. When exposing the nylon side of this material to HD, the nylon absorbed the HD and swelled. After evaporation of the HD, the physical properties of the original material were regained (i.e., any degradation of material properties are not permanent). When testing the nylon coated with fluoropolymer on both sides with HD, the breakthrough vapors were below detectable levels of $0.75 \mu\text{g}/\text{cm}^2$ for 72 hours. Decontaminating the exposed nylon side of HD using DS-2 resulted in only 2% of the agent being recovered following the decontamination.

The Kevlar®, Nomex®, and fiberglass laminates can be readily heat sealed together since these substrates can withstand the high temperatures required to heat seal the fluoropolymer (about 500° to 700 °F). The heat seals can be formed by heating aluminum blocks to the proper temperature and pressing the laminates together between the heated blocks using hydraulic or pneumatic cylinders. Custom-designed aluminum blocks for heat sealing curved hood pieces could be made. However, the nylon and polyester laminates can't be heat sealed on the fluoropolymer coated side since these fabric substrates will melt at the high temperatures. The nylon with fluoropolymer on one side can only be heat sealed on the non-fluoropolymer side only because this side of the laminate is coated with a polymer which can be heat sealed at temperatures of about 350°F. Chemfab is presently developing methods of heat sealing the nylon and polyester laminates by adding fluoropolymer coatings to the barrier coated sides which would allow these sides to be heat sealed at the lower temperatures. A sample of a heat seal covered with sealing tape was provided to Battelle where the polyester substrate was coated with the heat sealing fluoropolymer. However, the chemical barrier fluoropolymer coatings were not applied to this sample. Chemfab has expressed interest in fabricating heat sealed hoods for prototypes and is also interested in developing other materials, including a fluoropolymer/polymer laminate where the laminate would be thermoformable and the thin fluoropolymer would stretch during forming.

Some initial testing was performed on three Chemfab materials by CRDEC (ref 17). The testing was a standard liquid/vapor chemical agent penetration test for HD. The tested materials were STR 090591-D (167 minutes), MD-3 (69 minutes), and Challenge 4000 (76 minutes). These samples may have been handled roughly which could have shortened the breakthrough time. Other historical

facts of these samples were not known. Although this test data is important, additional well-documented testing may be warranted.

Barricade® is a multilayer fabric produced by Du Pont for use in protective apparel. Barricade® is available in yellow and green colors.(ref 18) This material provides over 20 hours of breakthrough time for HD.(ref 6) A large sample of Barricade® was given to Battelle for evaluation. This material seems strong and durable, but it is very stiff and would not likely make a conformal hood or facepiece. Barricade® was not considered for use in the LPM prototypes although it was used in the fabric hood mockup as the facepiece.

Tyvek®/Saranex® 23-P is a laminate of DuPont's Tyvek® and Dow Chemical's Saranex® 23-P film.(ref 18) This laminate is produced for use in chemical protective clothing. No sample was specifically obtained by Battelle; however, the literature states that a two-ply version of this laminate is available. For a number of the chemicals shown in the literature, the two-ply version increases the chemical breakthrough time by a factor of about 5 to 6 times. For some chemicals, this factor is as high as 10 or more.

3.2.1.2 Non-Fabric Films

Saran® is a good permeation barrier produced by Dow Chemical Co. Saranex® is a laminate of Saran® sandwiched by low density polyethylene (LDPE) and ethylene vinyl acetate (EVA) also produced by Dow Chemical Co. The Saranex® film generally comes in thickness of about 3 to 4 mils with the latter thickness obtained by Battelle for evaluation. It was decided that Saranex® would likely not be strong enough for a facepiece or hood by itself. Saran® film having a 6-mil thickness was obtained for evaluation by Battelle. Although this film is thin, the strength properties were approaching that acceptable for LPM prototyping. Both of these materials can be thermoformed and heat sealed. However, the 6-mil thick Saran® could not be thermoformed successfully during testing at Battelle. After discussions with the supplier, it was determined that this material was fabricated by a blown film method which orients the material (i.e., frozen-in stretch). The resulting material is not thermoformable.(ref 19) Saran® is thermoformable when produced by casting, but a sample source could not be identified for Saran® in thicknesses of 6 mils or greater. Saran® was also not recommended as a multiple use item for chemical agent protection, but it could be used as a disposable item.(ref 19)

Teflon® is a chemical resistant material produced by Du Pont. Variations of this material in thicknesses of 1 mil have provided chemical agent breakthrough times for HD in excess of 24 hours (refer to Appendix B). Teflon® is very strong and flexible (in thin films), but it is not stretchy. Teflon® FEP, besides being very transparent, can be thermoformed and heat sealed. However, adhesives generally will not bond to this material unless the surface is first treated, such as a corona treatment or a chemical etching. Chemfab has produced visors for protective clothing from 10-mil thick Teflon® FEP.(ref 20) However, their experience is that FEP stress whitens, followed by cracking, if it is folded repeatedly.

Kraton® is a flexible and stretchy thermoplastic elastomer produced by Shell Chemical Co.(ref 4) It is soft to the skin and can be blow-molded into a foam. Although it alone does not provide a good chemical barrier, it might possibly be used in a laminate with a good chemical barrier which could then be thermoformed and heat sealed. A commercially available Kraton® laminate which could meet this description was not identified, but it may be possible to develop this laminate.

3.2.1.3 Elastomeric Materials

Elastomeric materials could be used to form a hood and facepiece. However, stretchy elastomers generally do not provide good chemical agent permeation resistance due to the same properties that provide the high degree of stretch. For increased strength, elastomers are formed onto fabric substrates. These substrates, in many cases, limit the stretch of the elastomer to prevent the material from exceeding its allowable tensile stress (i.e., rupture).

Two latexes were found to provide over 20 hours before breakthrough of HD during previous testing.(ref 6) These latexes were formed by evenly mixing Butyl Latex BL-100 (Appendix D, no. 32) with natural rubber latex 104L (Firestone), and by evenly mixing polyisobutylene latex (PIB-500) with natural rubber latex 104L. The samples provided by CRDEC were stretchy, but very tacky. BL-100 and natural rubber latex 104L were obtained by Battelle for dip-coat testing. This testing resulted in samples with only minimal tear strength and was not incorporated into a hood/mask prototype. The latex compounding and testing is presented in Appendix F.

A fluoropolymer latex, TN Latex (Appendix D, no. 33) was obtained by Battelle for dip-coat testing. However, due to the unpromising agent test results of reference 5, no testing with this latex was performed.

A polyvinylidene chloride (i.e., Saran®-like) emulsion coating called Daran® was obtained by Battelle.(ref 21) This emulsion can be applied to provide a thin-film high barrier coating to paper, paperboard, and plastics. Although it actually is a thin coating, it is presented in this section since it is similar to the latexes. Some types of Daran® can be heat sealed while others can be used as a laminating adhesive. The applied Daran® can be air dried or oven dried.(ref 22) It should cure as an optically clear film; the presence of haze indicates water or other contaminant. Some samples were made where the Daran® was brushed onto thermoformed Kraton® and onto a nylon/Lycra® fabric hood without success. Both samples resulted in hazy coatings. The Daran® did not adhere to the Kraton®, possibly due to the presence of contaminants or because a primer may be needed for bonding. The Daran® also did not bond well to the fabric hood and it made the fabric very stiff.

Kalrez® is a perfluoroelastomer which combines the chemical resistance of Teflon® PTFE with the resilience of rubber. Kalrez® is produced by Du Pont. It is fabricated by compression molding or calendaring/extrusion methods; it can not be fabricated by injection molding, dip molding, laminating, or coating processes.(ref 23) In addition, Kalrez® bonds poorly and is not recommended for stitching or taping seams. Kalrez® does provide more than 20 hours breakthrough time for HD.(ref 5) A sample was provided by CRDEC which was very stretchy and strong. The biggest disadvantage of Kalrez® is the high cost and availability. The largest size which can be made at the present is 6 inches by 24 inches. A 0.010-inch thick sample of this size would cost about \$700.(ref 23) After some development work, large quantities (i.e., 100,000 pieces) of 24-inch by 24-inch sheets may cost between \$1500 and \$2000 each.

3.2.1.4 Coatings

A number of material samples were obtained by Battelle from CQ Corporation. These materials consist of laminates where a foil layer is sandwiched by fabric layers. In general, foil layers provide excellent barrier properties, but these samples seemed to have pin-holes, either due to the fabrication process or lack of quality control. On some samples, the outer fabric would stretch so that excessive tensile stress would be applied to the foil layer, thus resulting in failure of the barrier. These materials had been tested by CRDEC for chemical agent permeation of HD and did not provide good barriers.(ref 6) Therefore, they were not considered for LPM prototyping.

A study was performed to investigate potential use of metalized low density polyethylene (LDPE) film in chemical protective clothing.(ref 24) The thickness of aluminum on the LDPE film was about 500 Angstroms. A problem with applying thin metalized film is that the aluminum is usually not 100 percent continuous, resulting in pinholes. The permeation rate may be significantly reduced by the metalized film, but the pinholes may eliminate any increase in the breakthrough time. Two layers of metalized film could be laminated together by bonding the two metal films together. Therefore, the pinholes will likely not align together. Testing found that the single metalized films increased the breakthrough times by a factor of about 4 over the non-metalized substrates. However, metalized film samples which were hand crinkled 5 times before testing did not show any improvement over the non-metalized samples.

Parylene conformal coating consists of a polymer series (para-xylylenes) developed by Union Carbide Corporation.(ref 25) Parylene is a transparent coating applied by vapor deposition at a pressure of about 0.1 torr and at room temperature. Because it is applied in a gaseous phase, the coating occurs on all surfaces exposed to the vapor. The Parylene molecules are simultaneously absorbed and polymerized on the substrate surface. The resulting bond is a mechanical bond and is not due to a chemical reaction, allowing it to be applied to any number of materials. Common coating thickness, depending upon the substrate material, range from 0.1 microns to 0.002 inches. Parylene is commonly used to conformal coat printed circuit boards in accordance with MIL-I-46058C. In addition, it is used to coat voicemitters of the M17 protective mask to provide protection against the decontaminant DS-2.

A number of material samples were submitted to Nov-Tan Corporation for coating with Parylene.(ref 26) The size of the samples were limited to about 6 inches by 6 inches due to the size of the vapor deposition chamber available. Both fabric and polymer films were submitted, including:

- Fabric, Lycra®/nylon blend
- Woven cloth, 50% polyester and 50% cotton
- Aliphatic urethane, 0.060 inches thick
 - 60 Shore A
 - 80 Shore A
 - 50 Shore D

- Kraton®, 0.007 inches thick
- Kraton®/PE blend, 0.020 inches thick
- PET, 0.005 inches thick

The Lycra®/nylon material was provided as unstretched and stretched (20 percent) to determine if the fabric could be coated in a stretched configuration and then relaxed to the original dimensions. This approach assumed the coating to the stretched fabric would provide a continuous coating while providing a chemical barrier which would be stretchy (Parylene film by itself is not stretchy). Both the Lycra®/nylon and the polyester/cotton fabrics were coated on both sides with coating thicknesses of 2 μ m (0.00008 inches) and 0.0005 inches. All of the coated fabric samples were fairly stiff and air could be exhaled through them. The pre-stretched Lycra®/nylon samples did not relax to the original dimensions; they were "locked" into their stretched shape. The samples having a coating thickness of 0.0005 inches were fairly stiff; however, the Parylene did not seem to crack when the samples were gently folded.

The polymer films were coated on both sides with coating thicknesses of 0.0005 and 0.001 inches. As the substrates were flexed, the films would separate from the substrate and fill with air although the coatings did remain as an intact film. The stiffer polymers, both the 50 Shore D aliphatic urethane and the PET did resist delamination. However, this is more likely due to these samples having a greater resistance to bending than the other samples.

Coating plastic films with glass (silicon dioxide) is under current development for use in the food and medical packaging applications.(ref 27) The glass can be applied to the plastic film by vacuum deposition or by electron-beam deposition to a thickness between 500 and 1000 Angstroms. At this thickness, the barrier is maintained while the brittleness is eliminated. In addition to the barrier properties, the glass provides optical clarity. When used in a lamination which must resist abrasion, it is recommended that the glass layer be sandwiched between two layers of plastic film. Extreme flexing may also crack the glass coating.

Another glass-coating technology being developed is a quartz-like coating, QLP®, applied to plastic food packing containers, such as plastic soft drink bottles.(ref 28) Currently this coating is being applied to rigid (i.e., stiff) plastic containers. The coating thickness is about 1000 Angstroms and it is optically clear. This coating has increased permeation resistance about 3.7 times over non-coated samples. Durability testing was conducted where the coated plastic bottles were pressed flat, by hand, 20 times after which they were blown back to their original shapes. These

samples were then tested and found to have lost only about 20 percent of their barrier properties. Two coated soft drink bottles were provided to Battelle for evaluation. One coated bottle was pressed flat by hand with no apparent cracking. Because the QLF[®] coating requires a stiff substrate, it may be useful in the LPM as a lens coating. However, this coating was not considered for use in the hood or facepiece design.

3.2.2 Semi-Permeable/Carbon Materials

Semi-permeable materials (also referred to as breathable or porous materials) are beneficial to chemical protective clothing because they allow water vapor to pass through the chemical barrier while minimizing chemical agent permeation. In general, these materials consist of a liquid barrier and a chemical vapor absorption material (i.e. activated carbon). By allowing water vapor to pass from the wearer, through the chemical barrier, the physiological burden on the wearer is reduced.

Military chemical protection clothing is currently available which uses Quarpel-treated cloth, such a nylon, as an outer liquid barrier and an inner carbon-loaded cloth layer (produced by Blücher) for gas absorption. The military suit composite has a carbon loading of 180 gms/m² and has reportedly passed chemical agent falling drop tests with only 0.1 µg/cm² of agent penetrating in 24 hours. (ref 29) Blücher also produces a soft cotton material loaded with carbon spheres of various carbon loadings. This material is referred to as pajama (PJ) cloth where PJ11 has a carbon loading of 150 gms/m² and PJ7 has a carbon loading of 180 gms/m². This composite material can be fabricated into a hood by sewing the carbon layer directly to the Quarpel-treated cloth and then sewing the combined fabrics into a hood. The seams will have a double thickness, but the double thickness of carbon will provide additional gas absorption at the seams. A thermoplastic tape can also be heat applied to the seams. One concern about the semi-permeable chemical barriers is the application of pressure to liquid agents on the liquid barrier. Applying pressure to liquid chemical agents could force the liquid through the liquid barrier material and excessively load the carbon layer. An impermeable material could be applied, like a patch, over the liquid barrier in areas where pressure contact is likely.

Another type of liquid barrier material which allows water vapor penetration is a porous fluoropolymer membrane (e.g., expanded Teflon®, ePTFE) commonly used in sport clothing, such as GORE-TEX® produced by W.L. Gore & Associates. Combining this type of liquid barrier with a carbon-loaded layer could form a composite material useful in the LPM design.

3.2.3 Lens Materials and Coatings

Various lens materials could be implemented into the LPM design (ref's 4 and 5). Rigid lenses could best be made from polycarbonate and hardcoated for abrasion and chemical permeation resistance. Flexible lens materials include aliphatic urethanes and a transparent EPDM previously developed by Battelle. As discussed in Section 3.4.1.1, impact-resistant polycarbonate rigid lenses with a hardcoating was selected as the lens design for the LPM. Therefore, flexible lens materials were not investigated.

3.3 Initial Mockup Fabrication

An initial design was generated based on the literature provided at the beginning of the program. Feedback was obtained from CRDEC at the first progress review meeting. This feedback was used to refine the initial design and to fabricate "rough" mockups of some mask components. These mockups were made to test and evaluate ideas while also providing actual pieces for communicating design suggestions.

3.3.1 Initial Design

The initial design was based on a number of assumptions and goals, including:

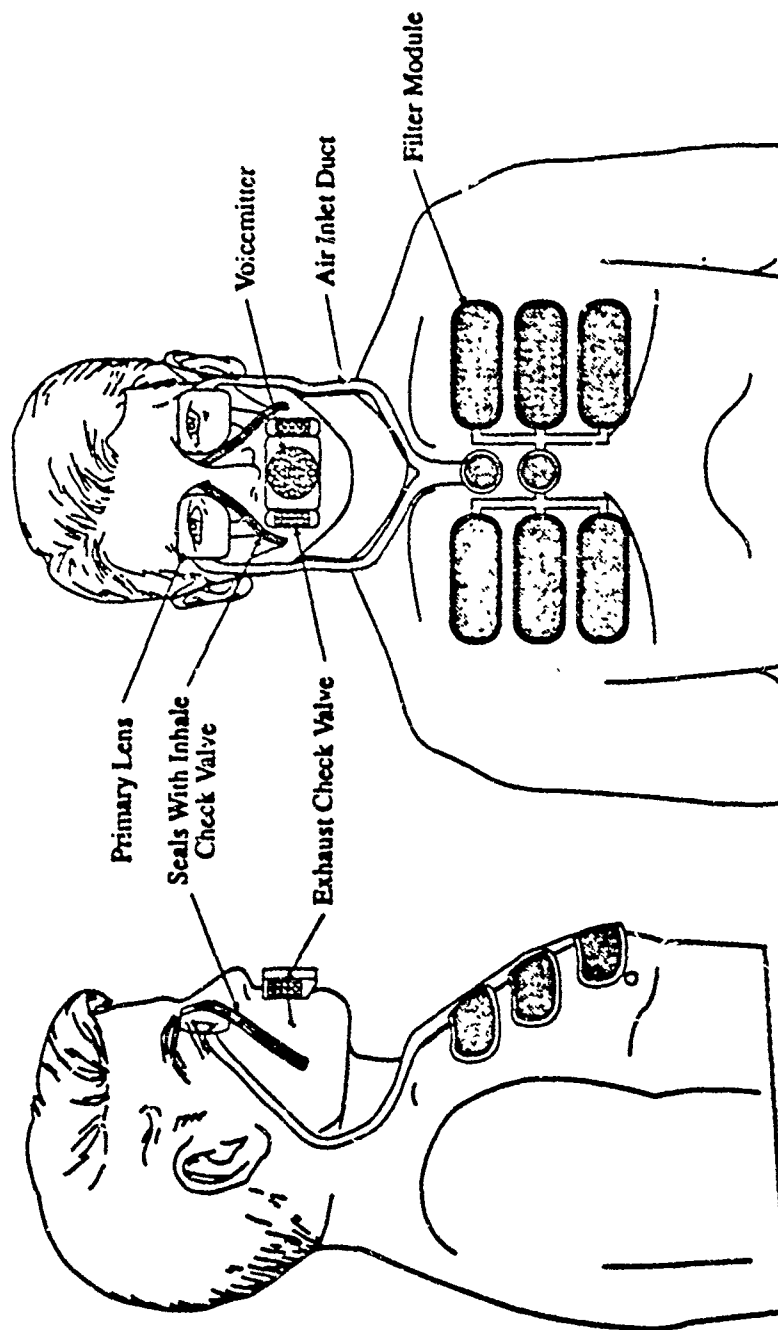
- The mask was to be low profile and lightweight. To help meet this goal, the primary lenses were assumed to be attached into a lens holder using adhesives or insert molded; a mechanical attachment/detachment method was not envisioned due to the likely larger volume and weight.

- The components should be designed for multiple uses to reduce the number of components and thus the overall size of the mask. For instance, the primary lens would be made out of rigid polycarbonate having a hardcoating instead of a flexible lens. This lens design would provide chemical agent protection while also providing ballistic protection. Also, the chemical barrier hood/facepiece should be made from a stretchy material allowing the hood and suspension to be integral. This stretchy barrier could also reduce the need for a peripheral face seal by tightly fitting to the face.
- Rectangular shaped inhalation and exhalation check valves might provide a lower profile than the standard round check valves without increasing the flow resistance.
- A voicemitter was to be included into the mask.

The drawings of the initial design are presented in Figures 2 and 3. Figure 2 shows the components basically hidden by the facepiece and hood, including the primary lenses and the air management components. Air inlet ducts, mounted on each side of the head, transfer air from the filters to the lens area for defogging purposes. The air then flows through a duct, a rectangular inhalation check valve mounted in a nose/mouth seal, and into the mouth area. The exhaust check valve is suspended from the facepiece which is not shown. The filter assembly is constructed of individual filter packets to facilitate folding of the filter assembly for storage. The filter ducts join a common connector which is not directly connected to the air inlet ducts. This design is to accommodate an optional blower for breathing assist. If a blower is not available, the two snap-fit connections would be joined with by a coupling duct which is not shown. Figure 3 shows the exterior features of the LPM. The front view includes a helmet which shows that the air inlet ducts mounted to the side of the head would not be pinched by the helmet chin strap and that the absence of a bulky nose cup does not inhibit the proper use of the chin strap.

3.3.2 Mockup and Testing

Initial mockup fabrication and testing was completed to determine basic properties of some component designs. Testing included measuring the air flow resistance of elastomeric tubes and check valves. Mockups were made of a dip-coat elastomeric mask and a non-stretchy fabric mask, including some initial lens designs.



Air Management Components Underneath Hood

FIGURE 2: INITIAL LPM DESIGN: AIR FLOW COMPONENTS

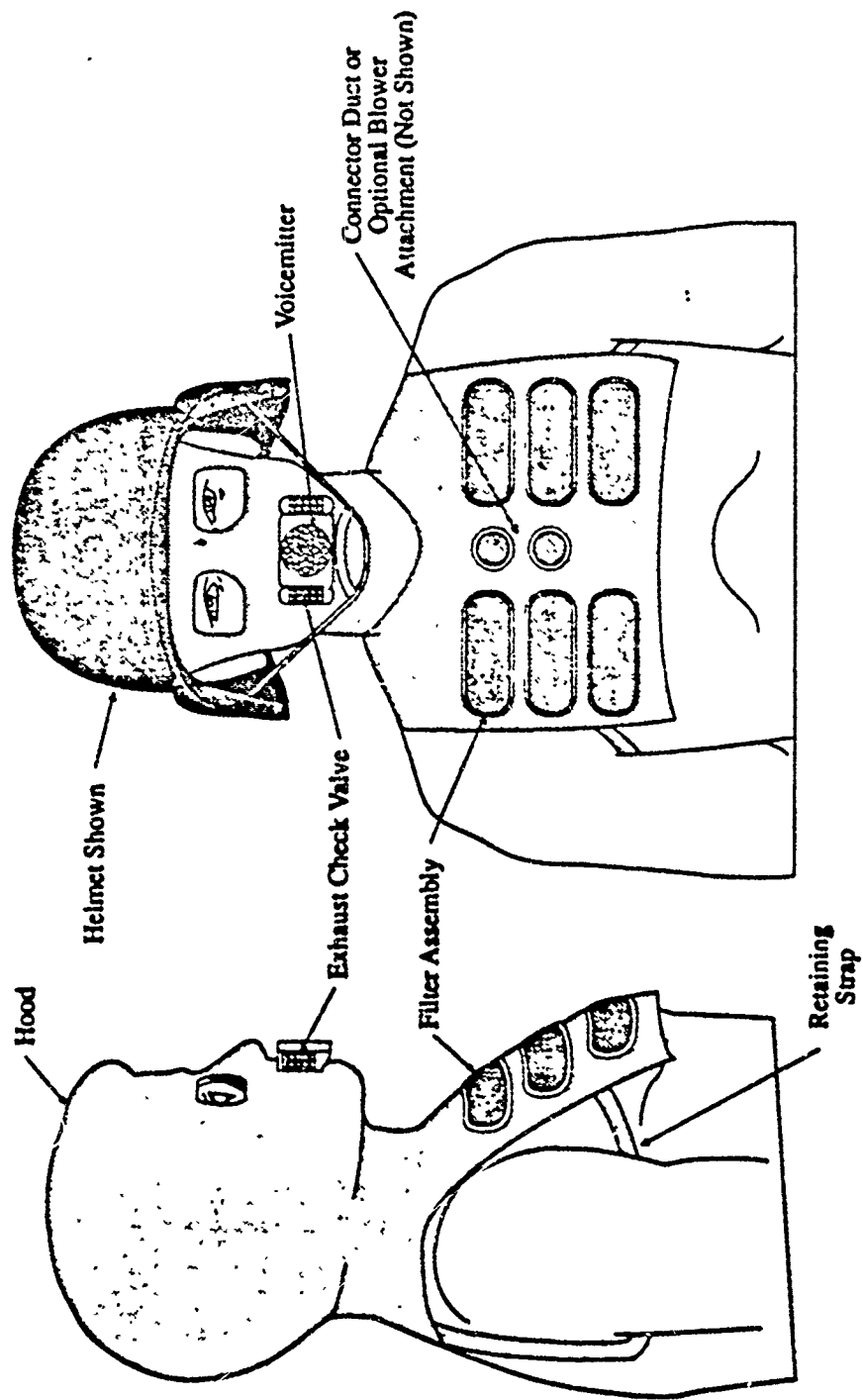


FIGURE 3: INITIAL LPM DESIGN: EXTERIOR FEATURES

3.3.2.1 Duct Pressure Drop Testing

To determine approximate duct flow areas to provide minimal pressure drops, initial testing was made to measure the pressure drops through tubes of various diameters. Other requirements of the LPM air ducts are that they are to be foldable and yet not collapse under slight vacuum pressures. Since the air ducts would likely be made from an elastomeric material to meet the foldability requirements, an effort was made to determine the effect of friction on the air flow through the tubes. Several types of materials were tested, including Tygon tubing, polypropylene tubing, and copper tubing. The copper tubing was tested as a control since it has a very smooth inner surface which minimizes the friction loss. Internal tube diameters tested were 0.25 inches, 0.38 inches, and 0.50 inches. The results of this testing are shown in Figures 4 through 6.

The pressure drop through a 0.375-inch inside diameter tube is approximately 10 mm H₂O per 2 feet of tube length (i.e., 5 mm H₂O per foot of length) for a flow rate of 42 lpm. This flow rate was used as the design flow rate since two tubes would likely be used in the LPM; one tube for each side of the face. The pressure drop through a 0.50-inch inside diameter tube is about 3 mm H₂O for a 2-foot length (i.e., 1.5 mm H₂O per foot of length) at a flow rate of 42 lpm. The cross-sectional area of the tube having a 0.38-inch inside diameter is 0.11 in² while that for the 0.50-inch inside diameter tube is 0.20 in². Because the air inlet ducts are expected to be only about one foot long each and 1.5 mm H₂O is a small percentage of the overall expected pressure drop during inhalation, 0.20 in² was selected as the design goal for air flow cross-sections. A duct for transferring air from the lenses to the mouth area could have a smaller cross-sectional area without a significant increase in flow resistance since the length is very short. A slight increase in pressure drop will likely occur for the design goal area if the cross-section of the duct is non-circular since the contact area will be larger (i.e., the cross-sectional perimeter will be larger). Also, tight bends in the ducts will also increase the pressure drop.

3.3.2.2 Check Valves

A number of current military check valve assemblies were provided by CRDEC, including the C15 and C23. These check valves are shown in Figure 7, along with a commercially available spiral check valve (Rudolph valve) and flat flapper valve (Survivair).

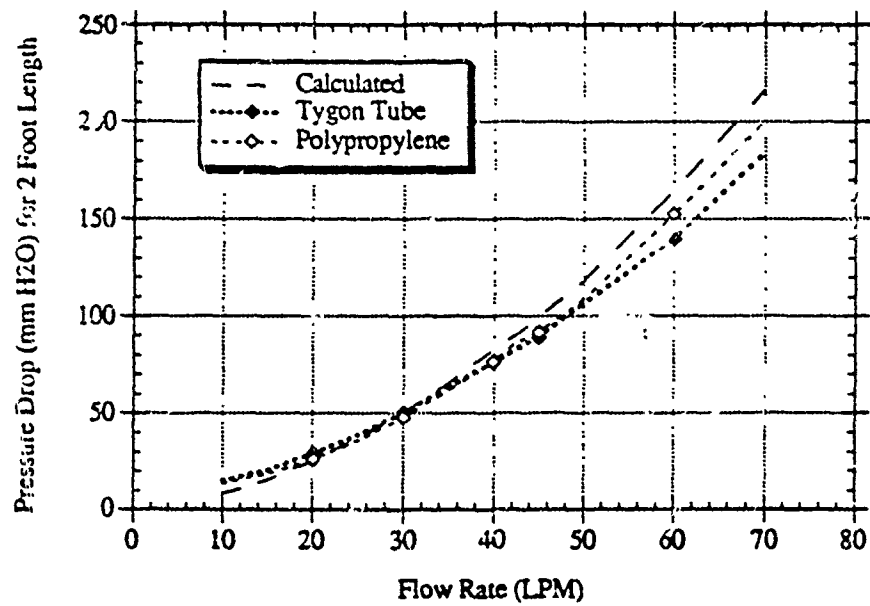


FIGURE 4. TUBE TESTING: 0.25-INCH I.D.

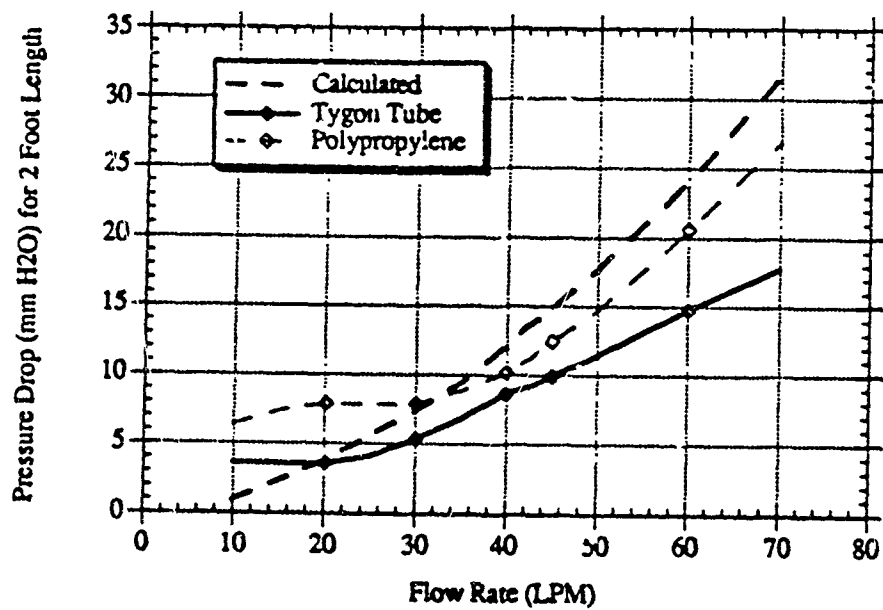


FIGURE 5. TUBE TESTING: 0.38-INCH I.D.

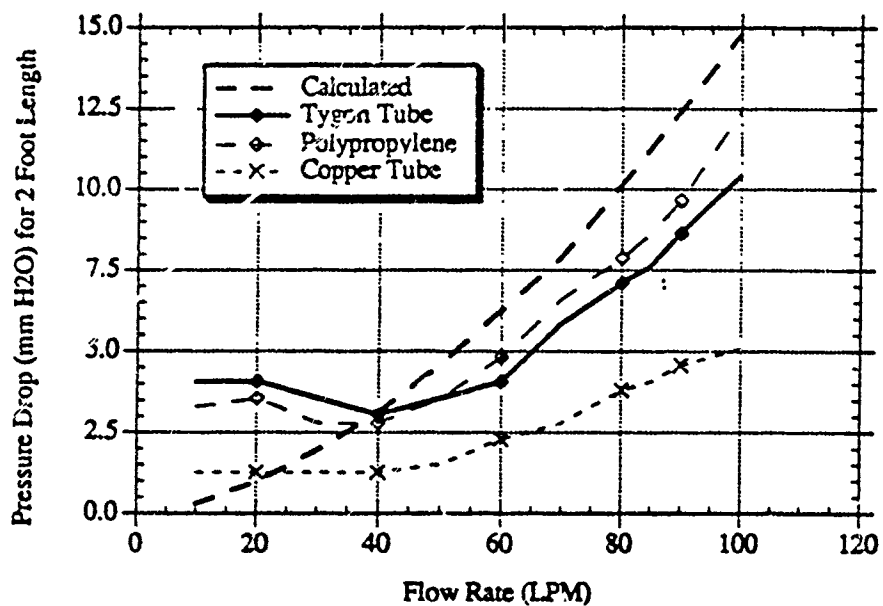


FIGURE 6. TUBE TESTING: 0.50-INCH I.D.

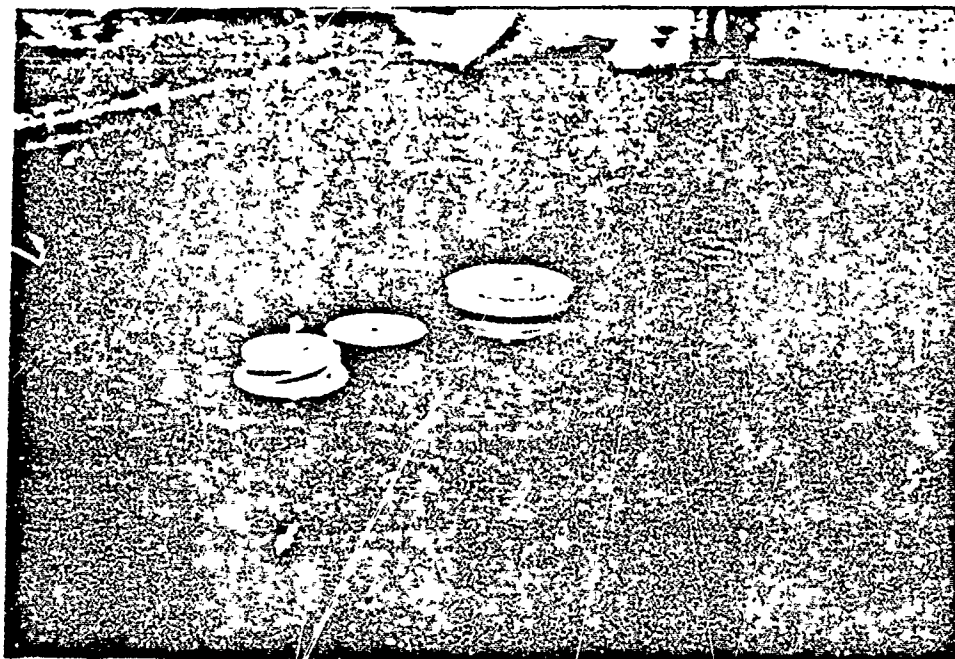


FIGURE 7. CURRENTLY AVAILABLE CHECK VALVES

All of the check valves used in protective masks seemed to be round designs. This uniformity in design could be the result of better performance and simplicity of manufacturing. Since a basic LPM requirement is for a low profile, using a rectangular check valve design was investigated. The basic principle of the flapper check valve is that air pressure is uniformly distributed on the flapper surface which acts like a cantilevered beam; the flapper is supported at the center and the unsupported end deflects to open up a flow path. The amount of pressure needed to provide a specific amount of air flow is proportional to the beam stiffness and the beam width. The beam stiffness is a function of the material stiffness, the beam thickness, and the length of the beam to the fourth power. Because the length of the beam has such a large impact on the force required, it was felt that a hinged rectangular check valve having a hinge length longer than the radius of a comparable round check valve could provide comparable or less pressure drop while providing a smaller profile. A rectangular check valve design compared to the C23 check valve is shown in Figure 8. The rectangular check valve could also be placed perpendicular to the air flow which can provide a smoother flow path, where the round check valve would have to be placed almost parallel to the flow path to achieve a low profile. To test the performance of rectangular check valves, the check valves presented in Figure 9 were fabricated: a flapper attached with two pins resulting in a small flapper radius, a hinged flapper on a flat check valve seat, and a hinged flapper on a curved check valve seat. The pressure drop across these rectangular check valves are shown in Figure 10. Although the pressure drop across the flat hinged design is lower than the curved hinged design, the former did not effectively seal when exposed to backpressure. The slight curve on the curved hinged check valve seat tends to prestress the flapper into the closed position. This latter design can be found in Appendix C with test results compared to the C23 check valve shown in Figure 11.

CRDEC provided a test report to Battelle on various check valve designs (ref 12) along with samples of some check valves which they have found to provide the best performance. For the exhaust check valve, it was suggested that Battelle use a convoluted design made of silicone rubber. Two versions of the check valve flapper were provided to Battelle: the first flapper design used a pin for attaching (refer to Figure 12) while the second, and preferred, design snaps over a post on the check valve seat (refer to Figure 13). Although silicone rubber doesn't provide a good chemical barrier, a cover placed over the check valve prevents liquid chemical agent from falling directly on the silicone flapper. In addition, the cover provides a dead air space which is flushed with "clean" exhaled air. A dimensioned drawing of the convoluted check valve seat having the post attachment

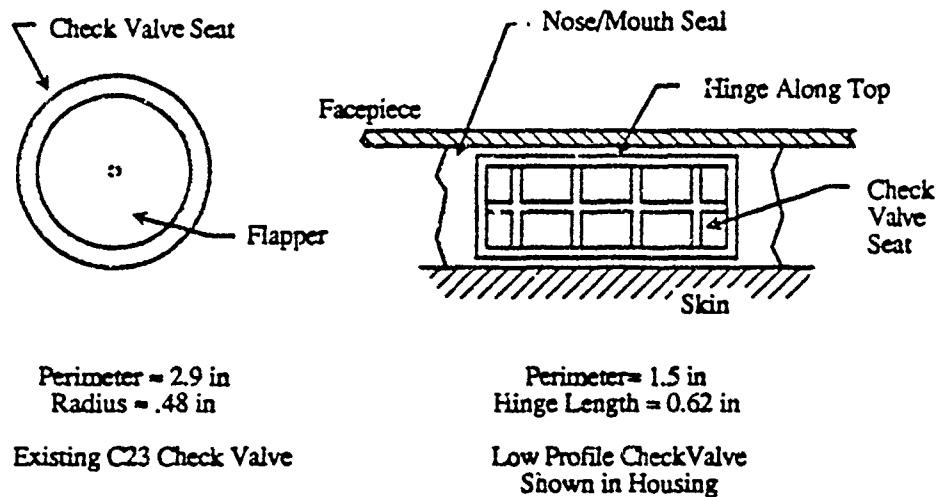
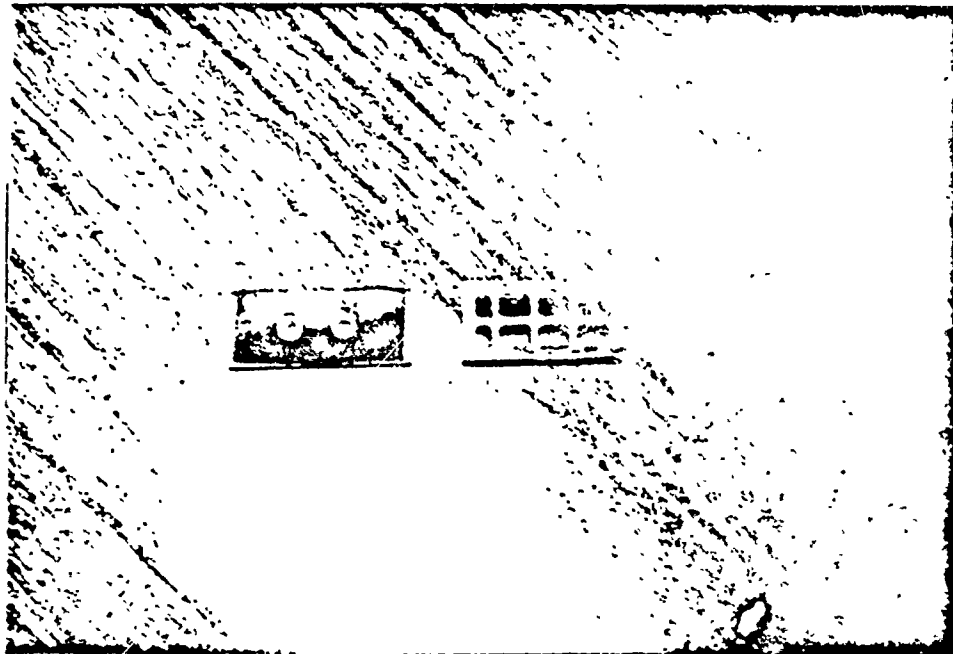


FIGURE 8. PROPOSED LOW PROFILE CHECK VALVE DESIGN

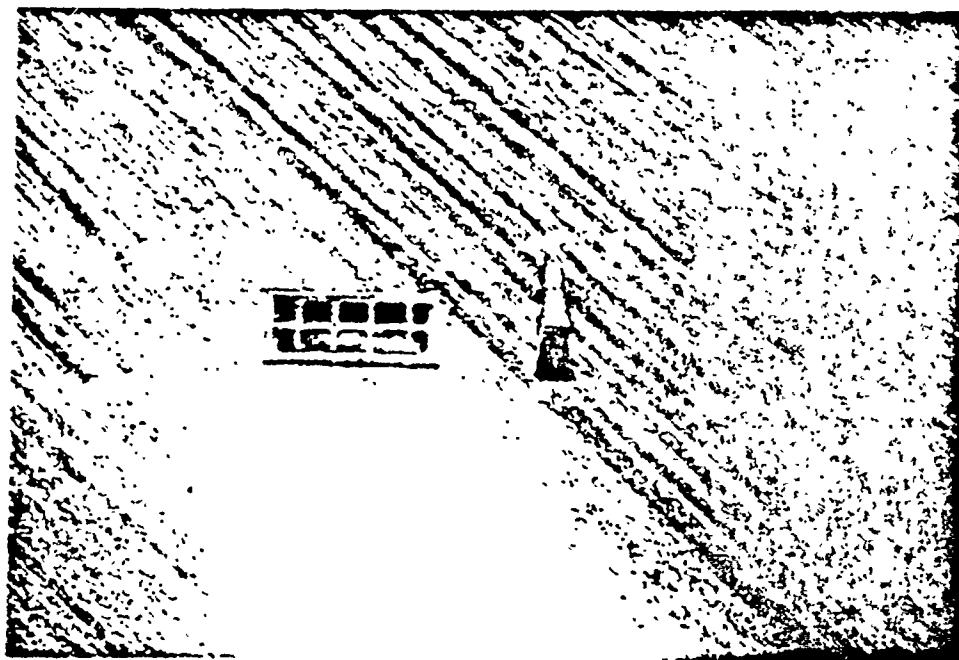
was provided to Battelle and can be found in Appendix C. For the inhalation check valve, CRDEC suggested using the existing C23 check valve.

3.3.2.3 Nose/Mouth Cup Seal

Suspension of the inhalation check valves in a nose/mouth seal as initially envisioned in Figure 2 was investigated. Mounting the inhalation check valves independent of the lens holders was felt to provide better folding properties. Some initial ideas were sculpted on a headform to suspend both the inhalation and exhalation check valves using the C23 check valve. The headform used was provided by CRDEC. Each concept was sculpted on only one side of the face to reduce the time required. Photographs were then taken of each concept; however, for clarity purposes, the photographs were reduced to line drawings. The primary functions of the nose/mouth seal are:



2-PIN



CURVED HINGE

FIGURE 9. RECTANGULAR CHECK VALVE DESIGNS

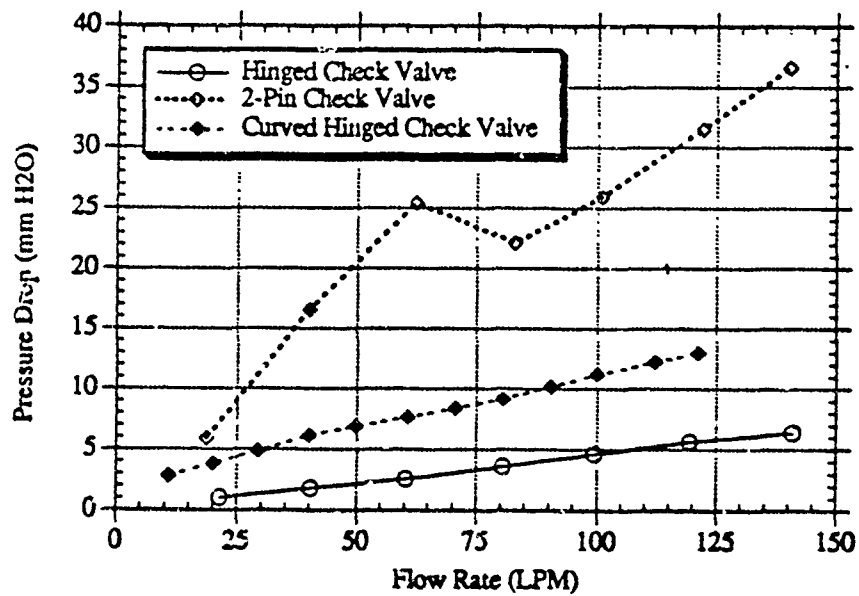


FIGURE 10. RECTANGULAR CHECK VALVE TEST DATA

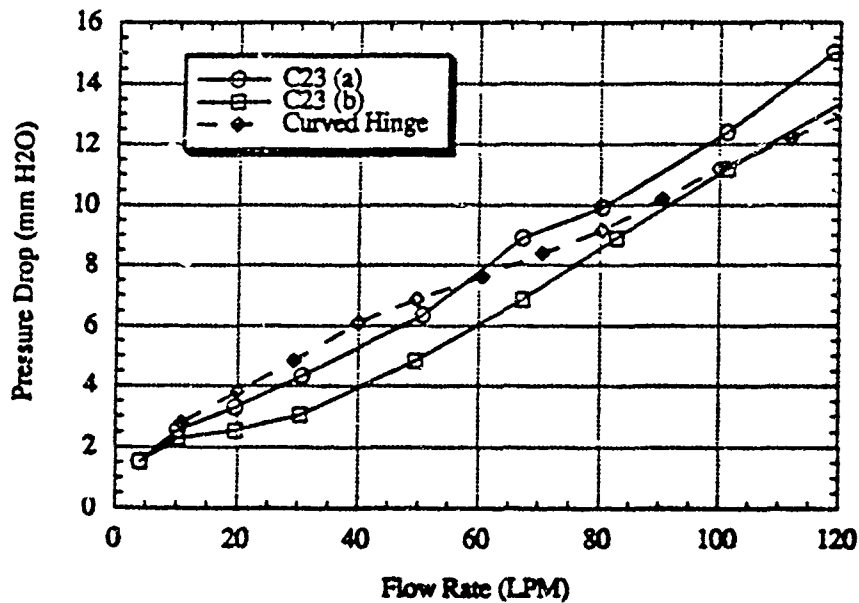


FIGURE 11. RECTANGULAR AND C23 CHECK VALVE TEST DATA

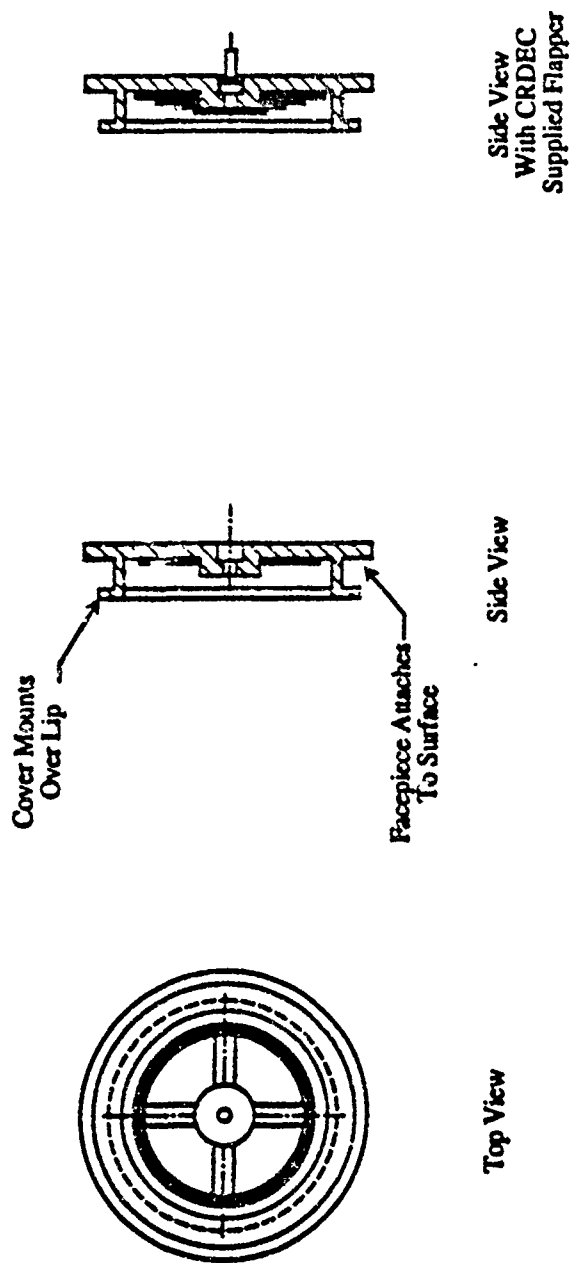


FIGURE 12. CONVOLUTED CHECK VALVE WITH PIN ATTACHMENT

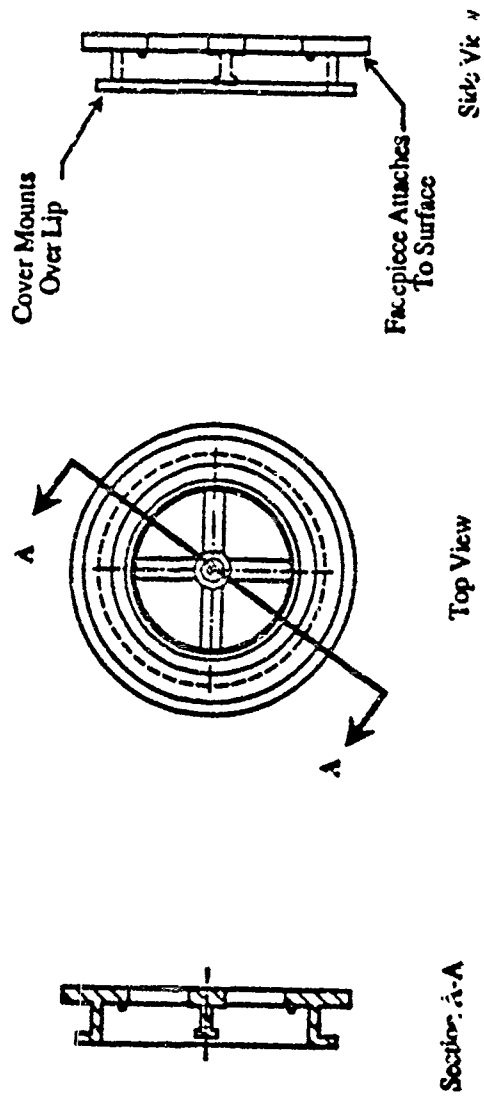


FIGURE 13. CONVOLUTED CHECK VALVE SEAT WITH POST ATTACHMENT

- To form a breathing compartment which would not exceed a volume of 50 milliliters to minimize CO₂ buildup (ref 12)
- To seal the lens compartment from exhaust air, thus preventing moist exhaled air from condensing on the lenses and preventing exhausted CO₂ from contaminating inhaled air.
- To not interfere with the wearer's mouth movement which could impede speech.

An open nosecup design, concept A, is shown in Figure 14. The open front reduces the nosecup weight without greatly impeding speech, but some billowing could occur during inhalation. The inhalation check valves, C23 check valves, are parallel to the face and are enclosed by the nosecup, positively forming an inhalation flow path. The facepiece would be bonded to the nosecup to complete the chemical barrier. The exhalation check valve would be mounted directly to the facepiece.

Nosecup concept B is presented in Figure 15. This closed design provides a positive standoff from the mouth which should not billow. The C23 inhalation check valves are not encapsulated by the nosecup and if the facepiece is not stiff enough, billowing could occur during inhalation. Besides generating a distracting noise, billowing would reduce the flow path size and increase the pressure drop. The C23 exhalation check valves are mounted to the nosecup. Two exhalation check valves are used to reduce the profile, but two covers would be needed to isolate these flappers from chemical agents.

Nosecup concepts C and D are shown in Figure 16. To provide a smaller nosecup size, the C23 inhalation check valves were mounted parallel to the side of the nose. Concept C is an open design with the inhalation check valve not enclosed by the nosecup. This mounting design could cause billowing of the facepiece which could result in the flow path being reduced and the pressure drop increased. The C23 exhalation check valve is mounted to the nosecup. The standoff in front of the mouth is open to minimize the degradation of speech transmittance. Concept D is like concept C except that the inhalation check valve is enclosed by the nosecup to preclude billowing.

3.3 2.4 Headform Fabrication

As mentioned in the previous section, a headform was provided by CRDEC. However, the specifications of this headform in terms of a 50 percentile male were not known. Therefore, a headform of the front half of human head was made to best meet a 50 percentile male head. The 50

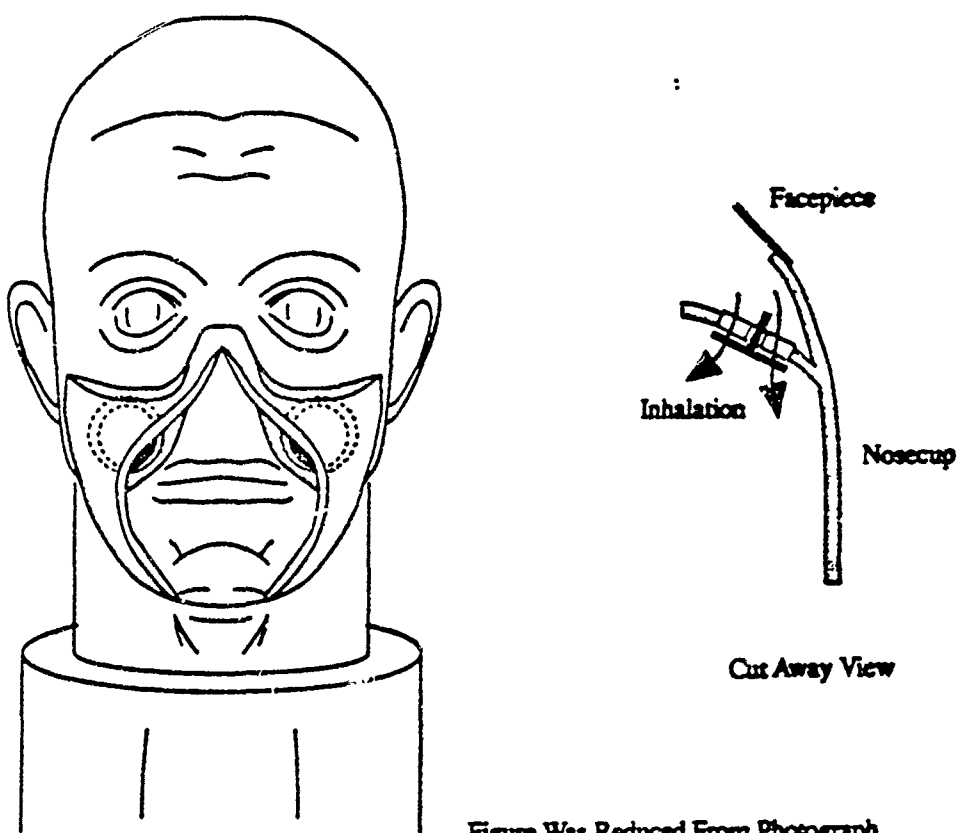


Figure Was Reduced From Photograph

FIGURE 14. NOSECUP CONCEPT A

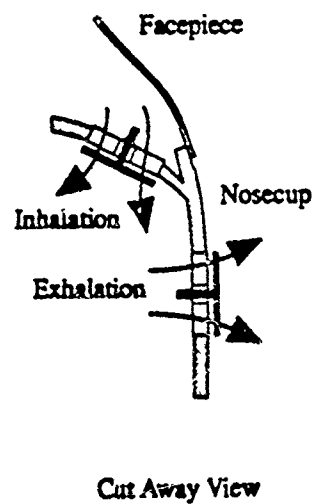
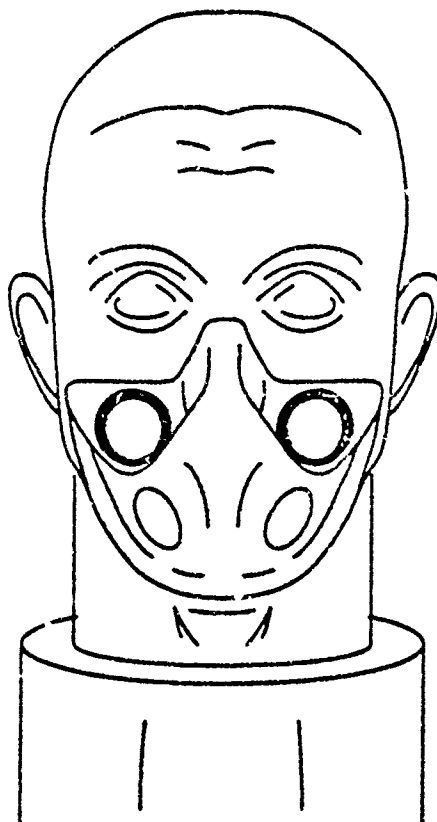


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FIGURE 15. NOSECUP CONCEPT B

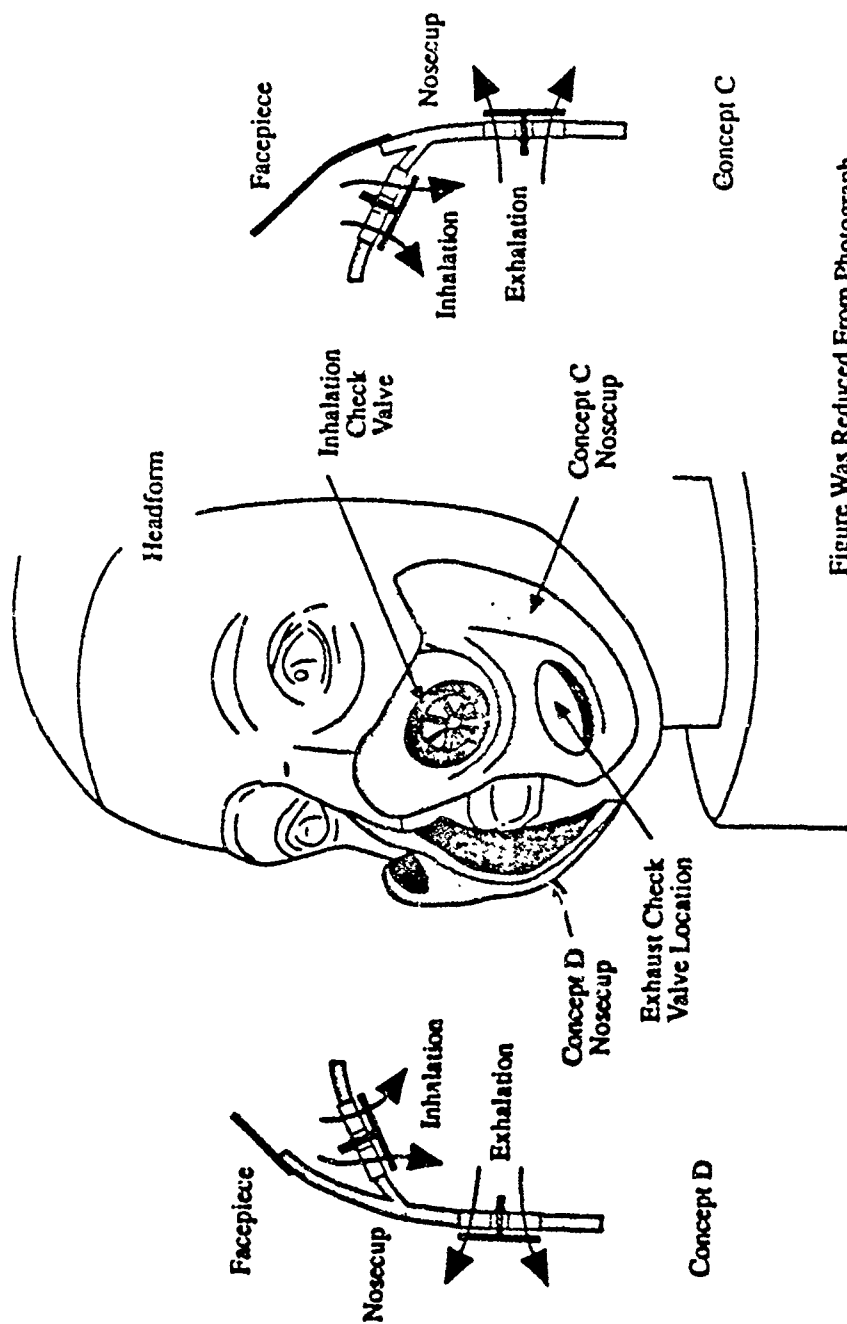


Figure Was Reduced From Photograph

FIGURE 16. NOSECUP CONCEPTS C AND D

percentile head dimensions were based on the averages of several anthropometric studies of similar populations and available headforms. The primary study used was based on a survey of U.S. Air Force personnel (ref 30). Reference 30 contains data from other studies of U. S. Army infantry troops, armored personnel, and aviators. MIL-STD-1472C was also consulted for anthropometric data which included a category for ground troops.(ref 31) A basic headform was then cast of a Battelle employee approximating the 50 percentile male data. Some measurements of this headform are presented in Appendix C along with some comparable dimensions.

To cast the basic headform, the subject's hair was covered with a bald wig piece and the eyebrows were coated with petroleum jelly. These measures were necessary to be able to release the subject from the mold. A quick-curing replicating material, Algi-Cast (Appendix D, no. 17), was mixed for use and applied as the subject's eyes and mouth were kept closed. The nasal passages were kept open for breathing purposes. The Algi-Cast was applied carefully to preclude trapping air and to replicate as much detail as possible. The Algi-Cast mold was then reinforced with plaster and quick-setting plaster bandages generally used for forming casts on broken bones. Because Algi-Cast is made from dry seaweed and will break down over time, a positive mold was then made with a permanent material. A female casting mold was then made of the permanent positive so that a number of headforms could be cast. The final headform is presented in Figure 17.

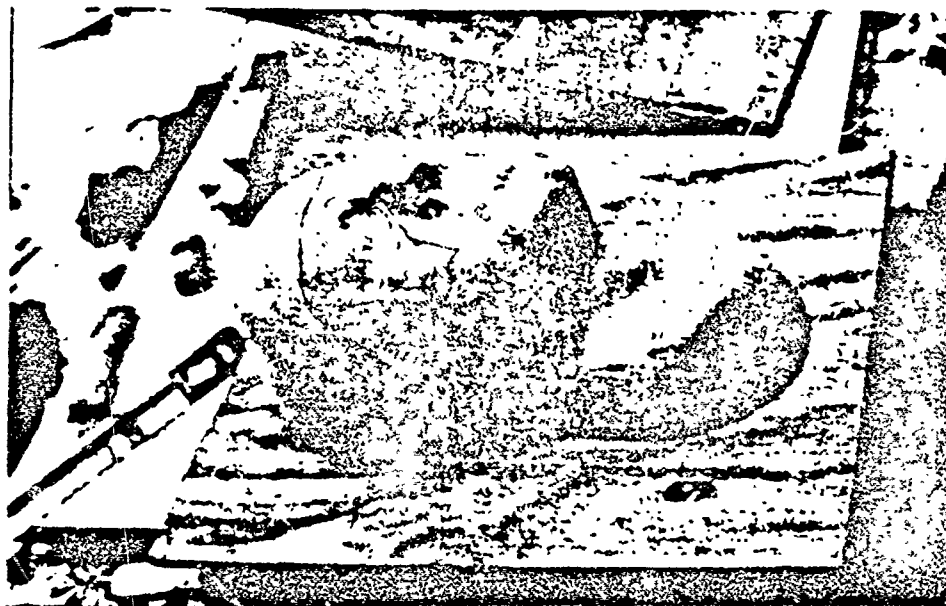


FIGURE 17. 50 PERCENTILE HEADFORM

3.3.2.5 Elastomeric Hood

A hood was fabricated from flat sheets of neoprene having a thickness of about 16 mils (0.016 inches). The neoprene was used to simulate Kalrez® (refer to Section 3.2.1.3) which was found to be a good chemical agent barrier. Edge joints were made by applying adhesive to neoprene strips placed on top of adjacent rubber pieces. This hood was not integrated with lenses or air management components, since this hood was basically made to get a feel for the characteristics of an elastic hood and facepiece. Kalrez® was initially being investigated because of its excellent chemical properties. However, as the cost of Kalrez® became known, it was determined that a cost-effective mask could not be made from this material in the near future. Development of the neoprene hood did result in a pattern for making a tight-fitting hood out of flat rubber sheet.

3.3.2.6 Dip-Coated Mask Mockup

A mockup was made to explore the dip-coated mask concept. This mockup, shown in Figure 18, included a urethane/fabric substrate hood and facepiece, a suspension, two primary lenses, a silicone lens holder, and Tygon tubing for air flow. The lenses and lens holder were taken from a SCUBA diving mask. The flat, glass lenses were replaced with acrylic lenses having the same area as the glass lenses and a thickness of 0.12 inches. The lens holder was a one-piece silicone rubber part with a nose cover. A fabric hood made of stretchy nylon/Lycra® was used as a substrate for the urethane coating. The urethane, Flexane Brushable Urethane (Appendix D, no. 25), was a brushable grade mixed with a flexing agent, Flex-Add (Appendix D, no. 26), which resulted in a hardness of about 55 Shore A. The intent of coating a flexible fabric with a stretchy elastomer was to integrate the facepiece, hood, and suspension into one piece. To facilitate donning and doffing while still providing a tight, conformal fit, pleats were placed at the back corners of the head. Tygon tubes were placed on the side of the head and into the outer sides of the lens holder. The construction of this mockup was as follows:

- The nylon/Lycra® fabric hood was fabricated by sewing two halves together with the seam running from the vertical center of the face to the back of the neck. This fabric hood was placed on the headform.
- Triangular plastic forms were attached in the back corners of the headform for generating the pleats. These forms were placed on top of the fabric hood.

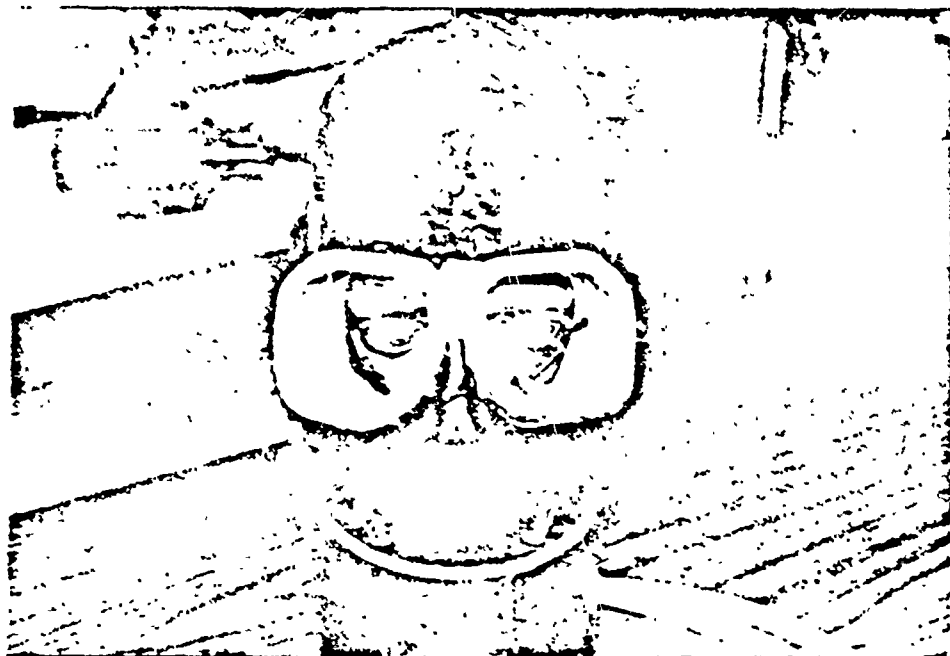


FIGURE 18. DIP-COATEL MASK MOCKUP

- The lens holder and lenses were placed on the headform.
- Two Tygon tubes, 0.38 inches inside diameter, were attached to the fabric hood to duct air from the chest area to the outer sides of the lens holder.
- The acrylic lenses were masked off.
- Nylon Lycra[®] fabric was fitted and attached to the Tygon tubing and the nose cover of the lens holder to form a nosecup.
- The Flexane Urethane was mixed with the Flex-Add and brushed onto the fabric hood and over the silicone lens holder. Because of the relatively short pot life of the urethane, only one, relatively thick coat (about 0.06 inches thick) of urethane was applied.
- After the mask was cured, air holes were punched in the lower part of the lens holder for inhaling air. The inner layer of fabric hood in the nosecup and inside the lens holder was removed.
- To complete the cure of the urethane and to increase the tack, the mask was baked in an oven at about 120°F for several hours.

The principle of the adjustment pleats seemed to work; however, the pleat forms were placed on top of the fabric substrate, instead of under the fabric. The pleat forms also had relatively sharp corners which were not coated very well by the urethane; therefore, the urethane coating ripped fairly easily at the pleat lines. The pleats would have worked better if they did not contain sharp corners and if the fabric substrate covered the pleat forms to better support the urethane.

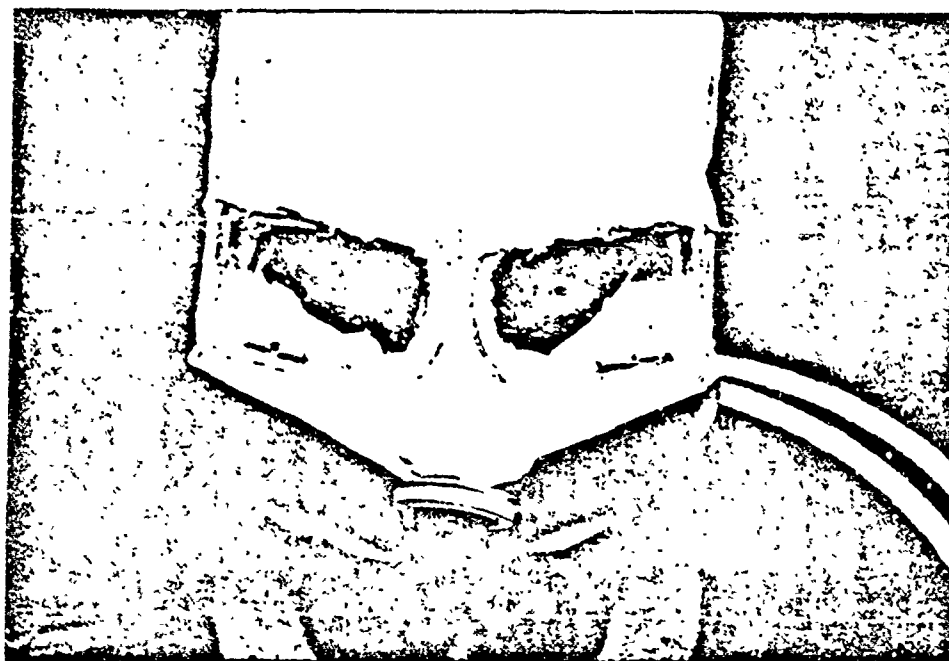
The lens shape and lens holder were borrowed from the dive mask to reduce the time needed to construct the mockup. These lenses had a large eye relief and they didn't provide any sideways vision.

3.3.2.7 Fabric Hood Mask Mockup

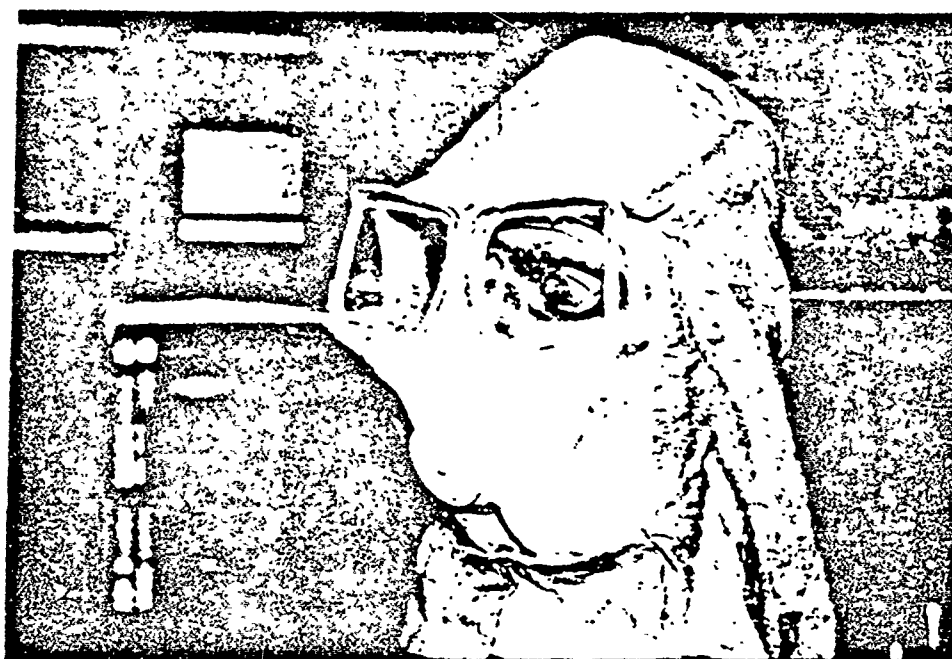
Following the dip-coated mask mockup, another mockup was fabricated to simulate a non-stretchy fabric hood and facepiece design. This mockup, shown in Figure 19, used the same lens holder and lenses as the dip-coated mask mockup with some changes. Inhalation check valve assemblies of the rectangular design were placed in the lower half of the lens holder. Flat side lenses were made of acrylic and attached to the outer sides of the acrylic primary lenses. The silicone lens holder was tailored to fit the new lenses by cutting and gluing. The hood was made from a non-stretchy, flexible coated fabric while the facepiece was made from Barricade® (DuPont) which is non-stretchy and somewhat flexible. A nylon/Lycra® fabric hood was used as the suspension. Tygon tubing ducted air into the lenses and also formed a face seal about the face. A Survivair check valve assembly was installed in front of the mouth for exhaling air.

The procedures used for fabricating this mockup were as follows:

- Two nylon/Lycra® fabric hoods were fabricated. Each hood was made by sewing two halves together with the seam running from the vertical center of the face to the back of the neck.
- The acrylic front and side lenses were made (refer to Figure 19) using the patterns presented in Appendix C. The side lenses were then glued to the front lenses.
- The silicone lens holder was cut and glued to provide a good fit with the acrylic lenses.
- Rectangular inhalation check valves (refer to Figure 20) were made where the check valve seat was acrylic and the flapper was 16-mil thick neoprene. The dimensions of the inhalation check valve are presented in Appendix C.



TOP VIEW



FRONT VIEW

FIGURE 19. FABRIC HOOD MASK MOCKUP

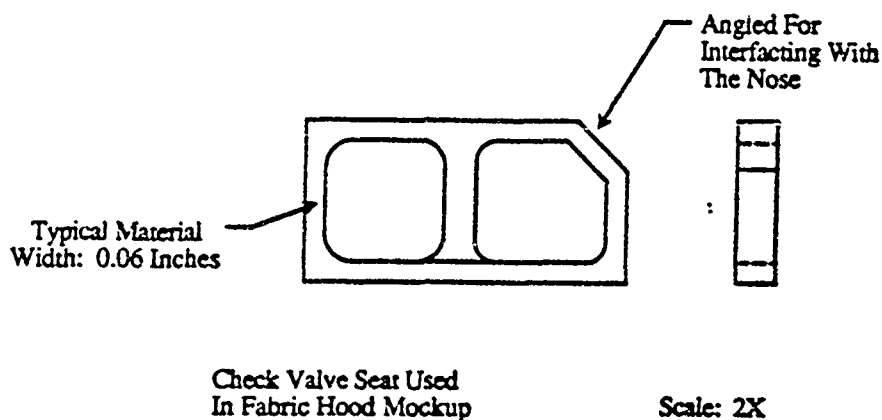


FIGURE 20. REDUCED SIZE RECTANGULAR CHECK VALVE

- The check valve assemblies were installed in the lens holder.
- The fabric hood was formed by sewing the coated fabric according to the pattern developed during the neoprene hood mockup. Like in the dip-coated mask mockup, pleats to facilitate donning and doffing were added to the back corners of the head. The hood only extended down to the shoulders due to the limitations of the headform used.
- One fabric hood was placed on the headform for use only as a construction aid.
- The lenses and lens holder were attached to the fabric hood.
- One Tygon tube, 0.38 inches inside diameter, was attached to form a loop from the chest area, over the lens holder, and back to the chest area. Another Tygon tube connected one side of the loop to the other side, passing underneath the chin. Together, these two tubes formed a simulated face seal/air inlet duct.
- The second fabric hood was placed over the lens holder and glued to the Tygon tubing, thus forming the suspension. The facepiece area of the suspension was cut out. The suspension was placed on top of the "face seal" so that the tension of the suspension pulled the face seal down onto the face.
- The Barricade® facepiece was cut to form the nosecup, attached with glue, and trimmed.

- The fabric hood was placed on the headform and glued onto the suspension. The mask mockup was then removed from the headform.
- The inner fabric hood was cut away from the mask and removed.
- A hole was cut in the Barricade[®] facepiece and the Survivair[®] check valve assembly installed.
- Holes were punched in the top of the lens holder and through the Tygon tubing for inhalation air.

The fit of the mask was basically good, but the lenses didn't provide sufficient field of view. The corner formed by the intersection of the front and side lens panels also protruded too far from the face. A redesign of the lenses would be required to minimize the eye relief and to decrease the profile while increasing the overall field of view. Drawings were made of an improved design where the front surface of the lenses had a very large radius of curvature (about 10 inches) with smaller radii on the outer sides of the lenses for a wrap-around effect (refer to Figure 21). The inhalation check valve assemblies were mounted to the lens holder. These assemblies were angled to lower the profile, but this action results in a smaller flow path. Optical correction inserts of -9.00 and +8.75 diopters are shown in the cross-section view. Although the design was improved over the flat lens design, the basic design did not seem capable of providing a low profile mask which could be easily folded while minimizing air flow restrictions and being durable. Even with the lower profile of the large radius lenses, it was apparent that the lenses would be too large. Also, the transition between the front and side lenses would be susceptible to breaking, such as that occurring at the bridge of the single-lens masks. The increased vertical height of the lens holder due to the check valve assemblies would impede folding for storage. Increasing the check valve cross-sectional area only compromises the lens profile and the eye relief. The curvature of the face, especially at the chin area, doesn't lend itself to a fabric facepiece. Pleats would have to be provided to accommodate the sharp curvature which would increase the difficulty in sealing the seams. Heat sealing the facepiece to the air management components would be made more difficult due to the raised portion of the pleats. Bonding these components with adhesive could best be accomplished by using a "thick film" adhesive which would seal around the pleat.

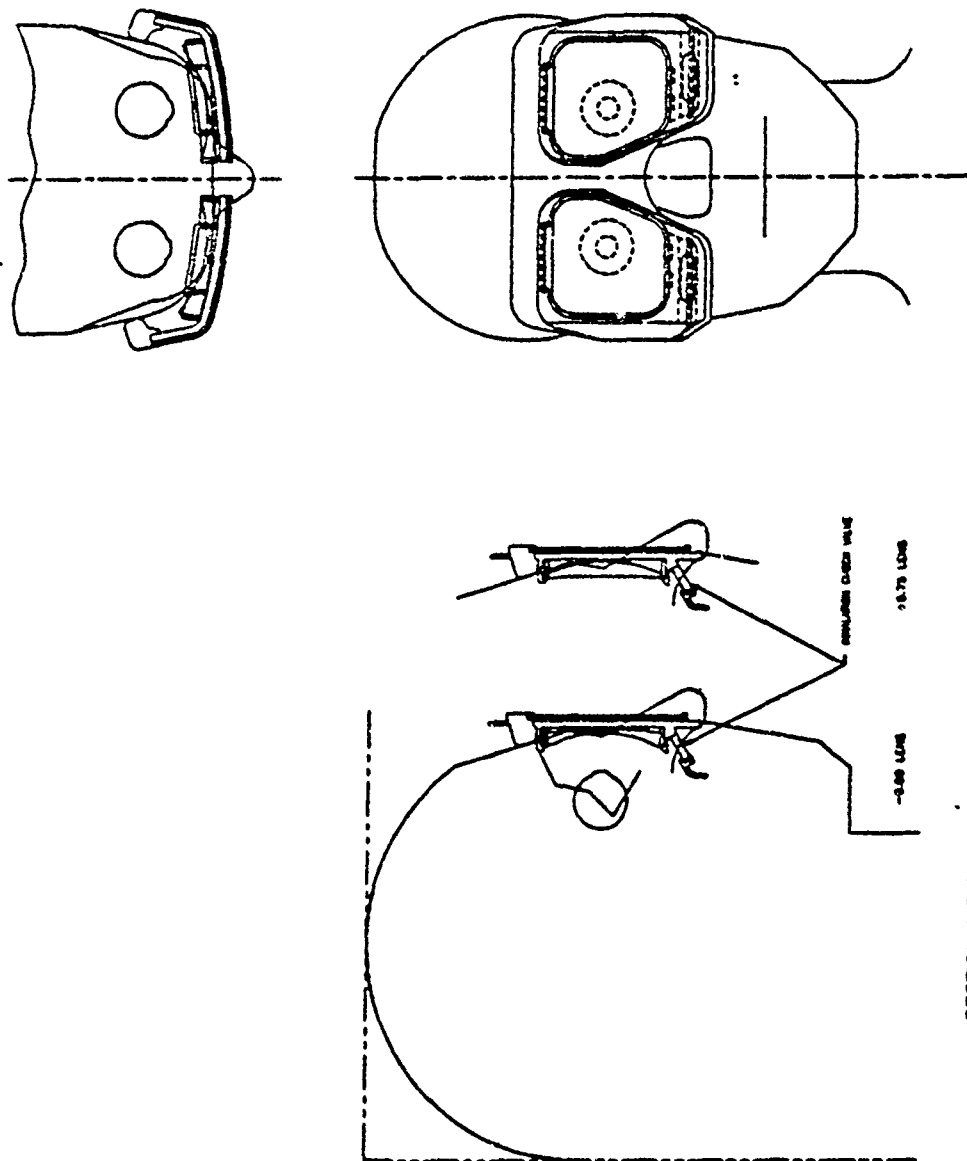


FIGURE 21. INTEGRATED LENS HOLDER/CHECK VALVE CONCEPT

3.3.3 Results of Mockups

The fabrication of the mockups generally identified design concepts which should not be pursued. For instance:

- The inhalation check valves should not be mounted directly to the lens holder since the low profile lens is a direct contradiction to increased flow area (i.e., decreased flow resistance).
- The added weight of a nose cup seal is undesirable and would likely decrease the ability to fold the LPM.
- Rectangular check valves show performance similar to the C23 check valves tested; however, if the rectangular check valve is located perpendicular to the face, the low profile is negatively impacted. The rectangular check valve can be angled relatively to the face, but the flow path area is decreased which results in higher flow resistance.
- An elastomeric facepiece/hood design is advantageous because a stretchy hood can provide better fit for a larger population size; however, adding a fabric substrate or increasing the hood thickness for the durability or for chemical protection required will decrease the stretchability.

3.4 Prototype Generation And Fabrication

The lessons learned during the mockup stage were used to develop a prototype design. The description of the design and fabrication for each component is presented separately below; however, these components were sculpted and molded in parallel due to time considerations. Changes which evolved in one component usually affected the adjacent components. Also, the tricks learned in molding one component usually benefited the molding of the successive components. For discussion purposes, the components are presented in the following groups:

- Lenses and lens holder
- Air management components
- Filter assembly

- Facepiece
- Hood
- Suspension

3.4.1 Lens System and Lens Holder

The visibility provided by a protective mask is one of the primary characteristics on which a mask is judged and accepted by the wearer. Vision acuity and field of view must be maximized to ensure that the soldier's mission can be accomplished. Therefore, the lens system and the lens holder were made the centerpiece of the LPM design with the other components designed to fit with the lens system. In the LPM, the lens system consists of primary lenses for chemical protection, optical correction inserts, and laser protection outserts. The basic design requirements for the lens system and lens holder are (refer to Appendix A):

- Provide chemical protection for 24 hours
- Withstand decontaminants and other chemicals, such as fuel and oil
- Provide an interpupillary distance of 57 mm (64 mm at the most) with the distance between lenses minimized (ref 32)
- Provide an eye relief (the distance between the pupil and the inner surface of the primary lens) of should optimally 18 mm and a maximum of 25 mm
- Provide impact resistance in accordance with ANSI Z87.1-1979
- Accommodate optical correction inserts having a minimum range of -7.00 diopters to +1.12 diopters.(ref 11)
- Ensure that the optical correction inserts and laser protection outserts do not require special tools for installing or removing.

To generate a lens design, a layout of the human eyes was made based on the requirements above and some assumptions. As shown in Figure 22, the center of eye rotation which is critical for vision acuity and field of view was taken to be 14 mm behind the corneal apex (ref 33). The stop distance (back pole of the lens to the center of rotation of the eye) is generally taken to be 25 mm for optical correction glasses. However, this results in an eye relief of only 11 mm (0.43 inches) while a minimum eye relief of 13 mm (0.50 inches) for anthropometric reasons in

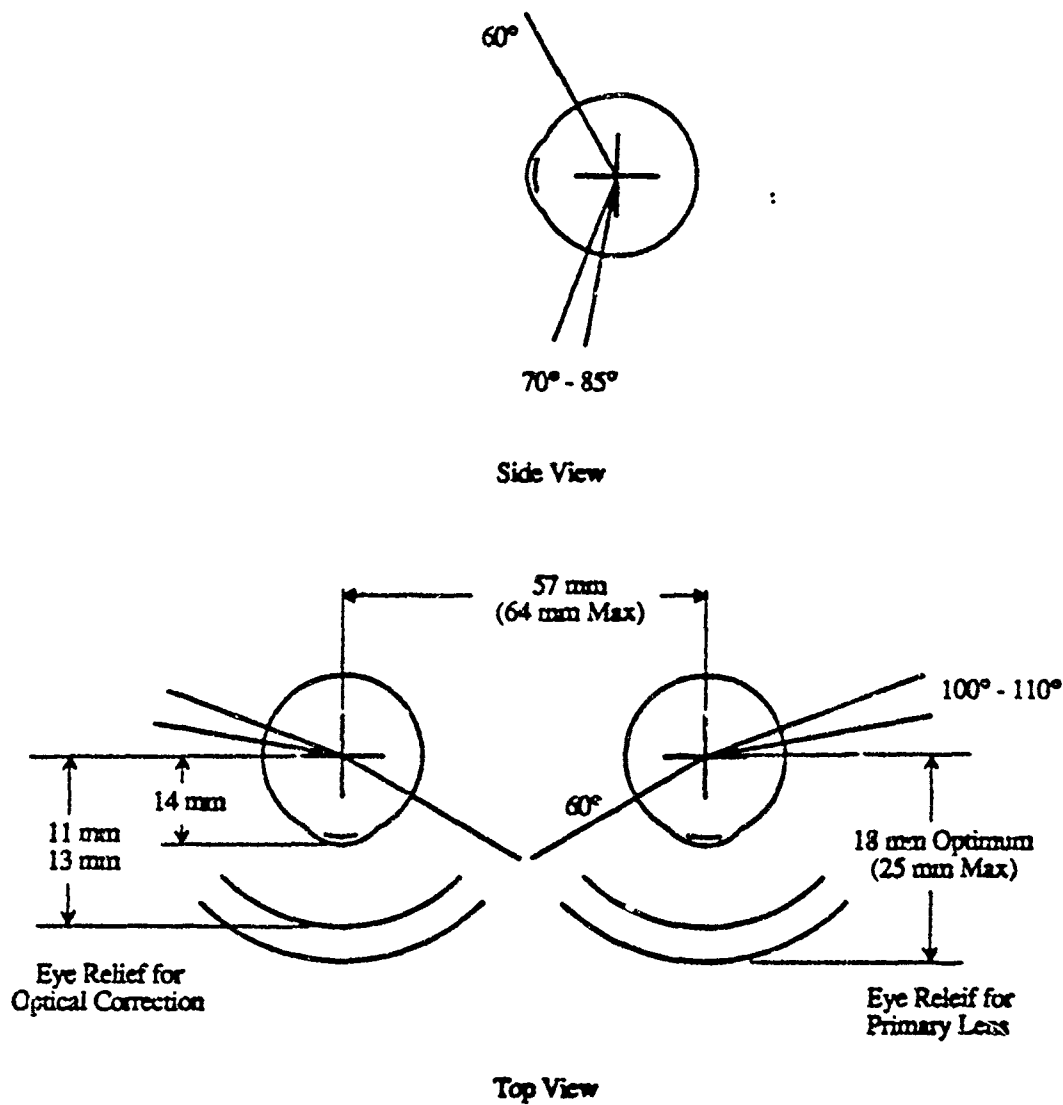


FIGURE 22. EYE LAYOUT

recommended in reference 10. The latter reference also states that current optical correction lenses are designed for a 9 mm to 15 mm standoff with a 5 degree pantoscopic tilt. Based on this information, the eye relief of the LPM was taken to be 0.50 inches. The normal field of view with a mask (ref 10) is also presented in Figure 22.

For maximizing vision acuity throughout the lens field of view, a number of design guidelines should be considered. Some of these guidelines are as follows;

- Optical aberrations should be made theoretically zero for the primary line of sight. They should also be minimized throughout the field of view to the degree possible as facial features and other mask components allow.
- The optic axis of the lens should pass through the center of rotation of the eye. When the visual axis and optic axis are coincident, the visual axis is perpendicular to both lens surfaces. For any other viewing angle, a lens designer is able to anticipate the specific location in the lens through which the visual axis will pass and by appropriate design, the designer can predict and control image quality.(ref 33)
- Lenses shall be as thin as possible and have a low refractive index to minimize distortion.
- Rigid lenses provide advantages over flexible lenses relative to optical quality, chemical resistance, impact resistance, and abrasion characteristics.(ref 10)
- The lenses should be as flat as possible to minimize eye relief. Also, a flat profile in the vertical meridian provides zero vertical prism, thus eliminating a cause of misjudging height and angular orientation with horizontal planes.(ref 8)
- The lenses should be rotated downward about 3° to reduce glare and glint. However, this rotation will result in a change of power, both spherical and cylindrical, if the optic axis fails to go through the center of rotation of the eye.(ref 33)
- Multiple lens surfaces increase the amount of lens refraction thus potentially creating ghost images. Anti-reflective coatings which are available will reduce this effect.(ref 10)
- Face-forming the lenses tends to cause the optic axes to rotate naselward. This action changes the performance of the lens, but it can be corrected by decentering both lenses outward so that the optic axis passes through the center of rotation of the eye. However, the combined rotation and decentering causes unwanted horizontal prism.(ref 33)

3.4.1.1 Primary Lens

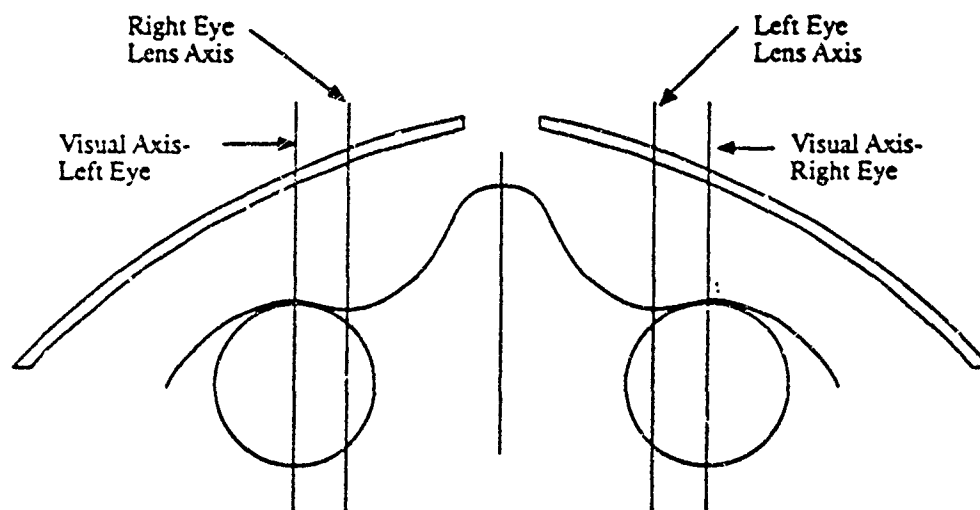
The primary lenses must provide the 24-hour chemical barrier required by the LPM. These lenses must also be foldable for easy storage. Because rigid single-lens windshield designs are susceptible to breaking at the nasal bridge, the primary lenses could be made from a flexible material, two separate lenses, or a rigid hinged design. The primary lenses must meet these requirements while not significantly degrading the wearer's visual acuity and depth of field.

Although ballistic protection is not a requirement of the primary lenses, it is a requirement of the LPM lens system. The basic design approach for the LPM has been to design multifunctional parts to reduce the number of parts, thus leading to less weight and lower profiles. Therefore, the decision was made early on to use two separate primary lenses made from hardcoated polycarbonate. The hardcoating is necessary for improving the abrasion resistance of polycarbonate. If the ballistic protection was not built into the primary lenses, it would either have to be provided by the laser protection outserts which may not always be worn, or by a separate additional lens. Other advantages of the selected design over flexible lenses are improved optical properties, improved chemical protection, and elimination of compression set (can occur to flexible lenses while folded). A hinged windshield design was not pursued since it was felt that sealing the hinge against chemical agent penetration would be difficult. The selected two separate polycarbonate lenses would be mounted in a flexible lens holder which allows folding between the lenses. The lens holder could also accommodate the mounting of both the optical correction inserts and laser protection outserts.

During a study of lens design (ref 8), a number of concepts for a primary lens were proposed and evaluated. These concepts will be discussed relative to the LPM design. All of the proposed concepts were flat in the vertical meridian. Concepts A and D had circular horizontal radii while concepts B and C had varying radii in the horizontal plane.

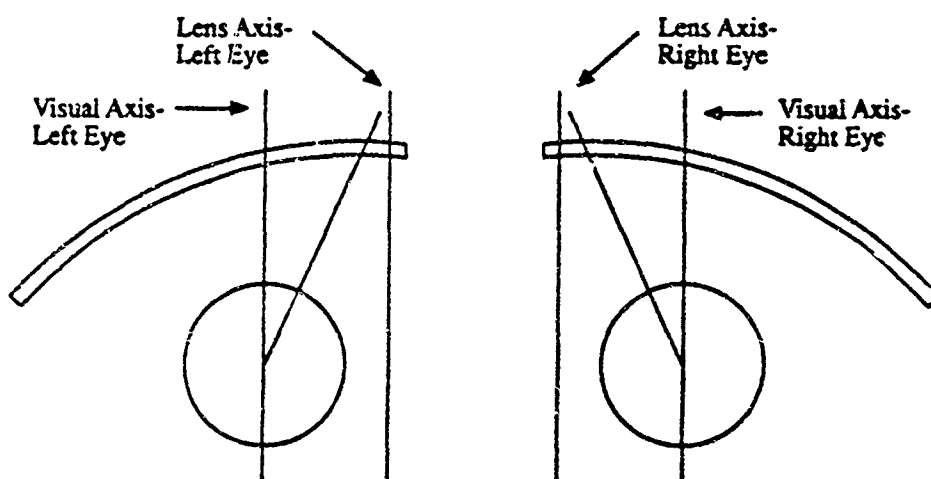
Concept A had a horizontal radius of 145 mm with a large decentration (refer to Figure 23). The optic axis for the right eye was located in front of the left eye and vice versa. Concept D, presented in Figure 24, consisted of two designs: one lens design had a horizontal radius of 58 mm while the other lens design had a radius of 76.2 mm. Both concept D lenses had moderate lens decentration with the 76.2 mm radius lens providing more clearance for combat spectacles. Also, the 76.2 radius lens provided better optical properties than the 58 mm lens.

Concept B was a one piece windshield design having a fairly flat front curvature and a steep wrap around curve at the outer periphery (refer to Figure 25). This one-piece design was not



Lens Radii: 145mm (5.7 inches)

FIGURE 23: CIRCULAR HORIZONTAL LENS: 145 MM (REF O)



Lens Radii: 58mm or 76.2mm

FIGURE 24: CIRCULAR HORIZONTAL LENS: 76.2 MM (REF O)



Primary Radius: 273 mm
Secondary Radii: 25.4 mm

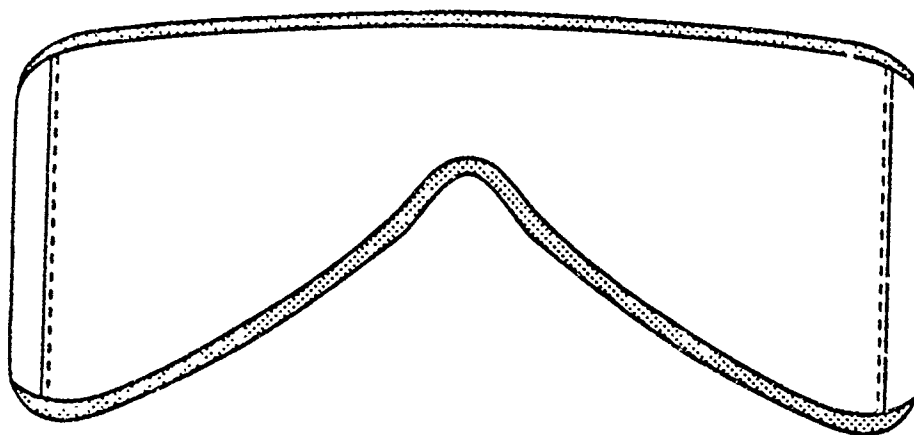


FIGURE 25: WINDSHIELD DESIGN, SINGLE LENS (REF 0)

considered for the LPM due to the increased chance of breaking; however, concept C was the same as concept B except that the windshield design was "cut" into two separate lenses.

Several primary lenses were provided by CRDEC for reference and possible use. One lens is used in the Aircrewman Protective Mask (ACPM) while the other is a lens system called the Protective Spectacles System (B/LPS).

The ACPM primary lens, presented in Figure 26, is a two lens design having a small size. Both the horizontal and vertical radii are relatively small. CRDEC has prototyped a corrective lens insert, also shown in Figure 26, for the ACPM lens. To provide a large field of view, this primary lens would have to be placed very close to the eye.

The B/LPS lens system is manufactured by American Optical Corp. (ref 34) and consists of a primary lens, corrective lenses, and laser protection (refer to Figure 27). The primary lens is a single lens design suspended by standard temples, nosepiece, and sideshields; however, these parts can be easily disassembled. The primary lens is made from polycarbonate. The optical correction lenses are mounted in a hinged carrier which is snapped into the back surface of the primary lens. The laser protection outsert is a green-colored single lens made of polycarbonate which mounts to the front surface of the primary lens. The profile of the laser protection outsert parallels the contour of the primary lens.

Some sportwear protective glasses were also purchased, including SCUBA diving goggles, swim goggles, water sport goggles, and general sport goggles. However, it was felt that the ACPM and B/LPS lenses were more suitable for the LPM design than these commercial lenses.

To facilitate prototyping of the LPM, it was decided to use an existing lens instead of forming a new design. The B/LPS lens was selected over the ACPM lens because the former was felt to provide a larger field of view, more suitable for corrective lens inserts, and the larger vertical radius better for vertical prism. Ten B/LPS systems were purchased with each system consisting of a clear primary lens system (i.e., temples, nosepiece, etc.), a bronze primary lens system, and one laser protection outsert. Because the primary lens is a one-piece design, the clear lenses had to be cut apart and shaped. These lenses were used in the final LPM prototypes.

The polycarbonate lenses would need to be hardcoated to withstand the abrasion and chemical permeation resistance requirements of the LPM. A number of hardcoating materials are presently available or being developed (ref 4), including Exxene Corporation's S-28 and S-30 Glass coatings, as discussed in Section 3.2.1.4, might also be used. Because hardcoating doesn't effect the

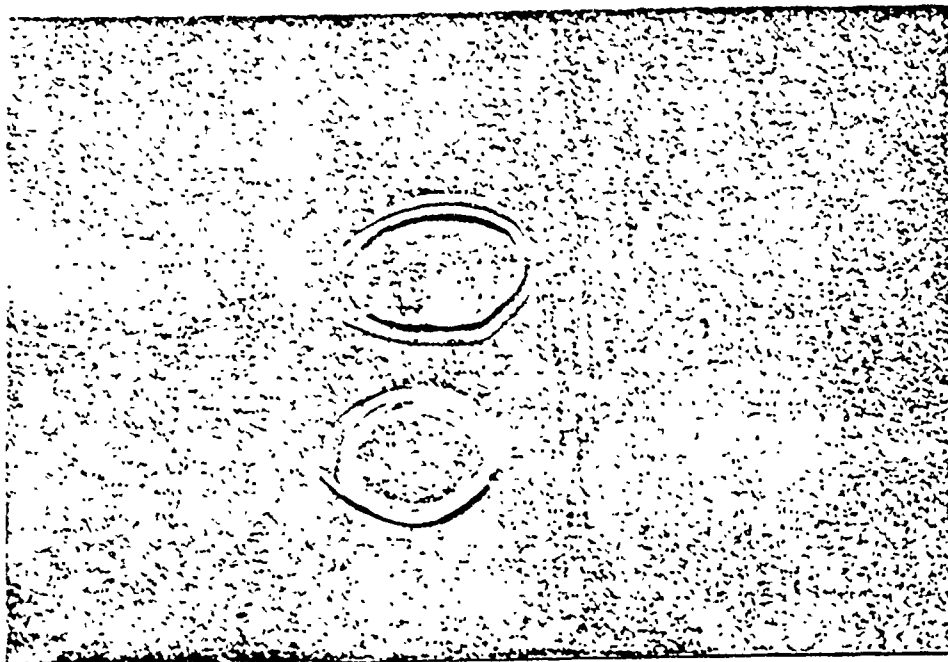


FIGURE 26. ACPM LENS WITH OPTICAL CORRECTION FRAME

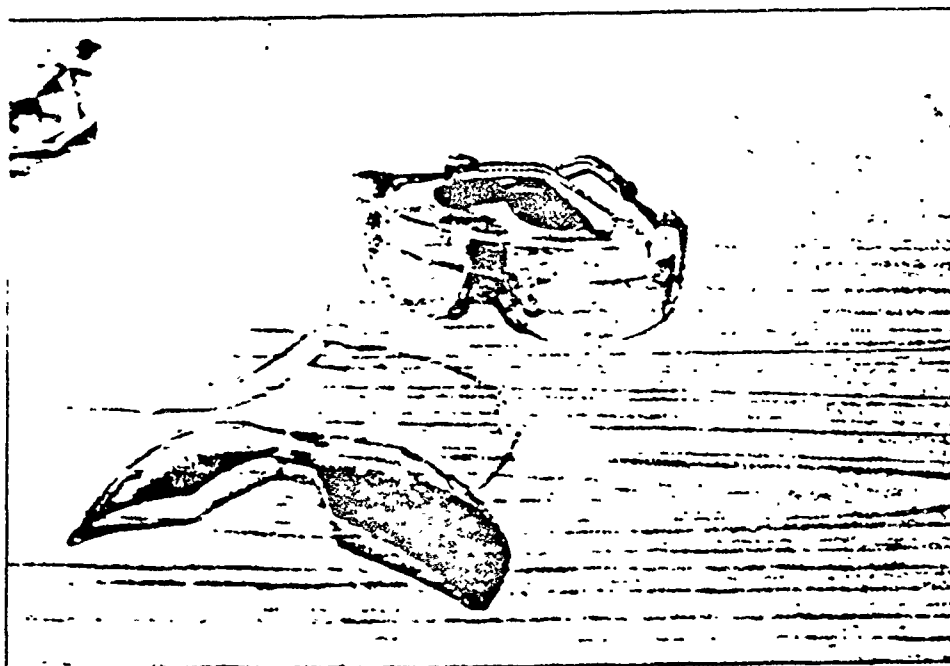


FIGURE 27. B/LPS LENS SYSTEM

basic functionality or appearance of the LPM prototypes, it was felt that the hardcoat could be better defined at a later development stage.

To improve the vision field of view provided by the B/LPS lenses, a new lens design was investigated. This new lens was designed based on the following guidelines:

- The vertical profile is flat to eliminate vertical prism and to minimize the eye relief. An added benefit is that the flat vertical profile simplifies lens fabrication since the curvature is in only one plane.
- The primary horizontal radius is 3.00 inches with the optical axis of the lens passing through the center of rotation of the eye. This horizontal geometry is shown in Figure 28. The 3.00 inches was the smallest radius felt possible which would provide sufficient clearance for the optical correction inserts. The range of optical correction was assumed to be -7.00 diopters to +2.00 diopters. The eye relief was taken as 0.75 inches.
- To provide a wide field of view and a close-fitting profile, a small horizontal radius was placed at the outer sides of the primary lens. To minimize distortion at the transition of the primary radius and this secondary radius, the tangent line of each radius was taken as coincident. Otherwise, the transition between the two radii would be visible to the wearer as occurring in some single-lens safety glasses.
- To make sure that the wearer's two eyes were looking through the same angle with respect to the lens surface, the primary radius was extended out to the same angle which could be seen by the other eye. In other words, the inward field of view of 60° was taken to be the outward angle in which the primary radius and the secondary radius shared a common tangent line.
- The secondary radius was selected to provide sufficient clearance between the outer edge of the lens and the wearer's head for the lens holder and inlet air duct.
- The lens is made from polycarbonate having a thickness of 0.12 inches. This thickness was selected because at least 3 mm (0.118 inches) are recommended to meet the impact resistance of ANSI Z87.1-1979 (ref 33 and 0.12 inches is a readily available thickness for thermoforming).

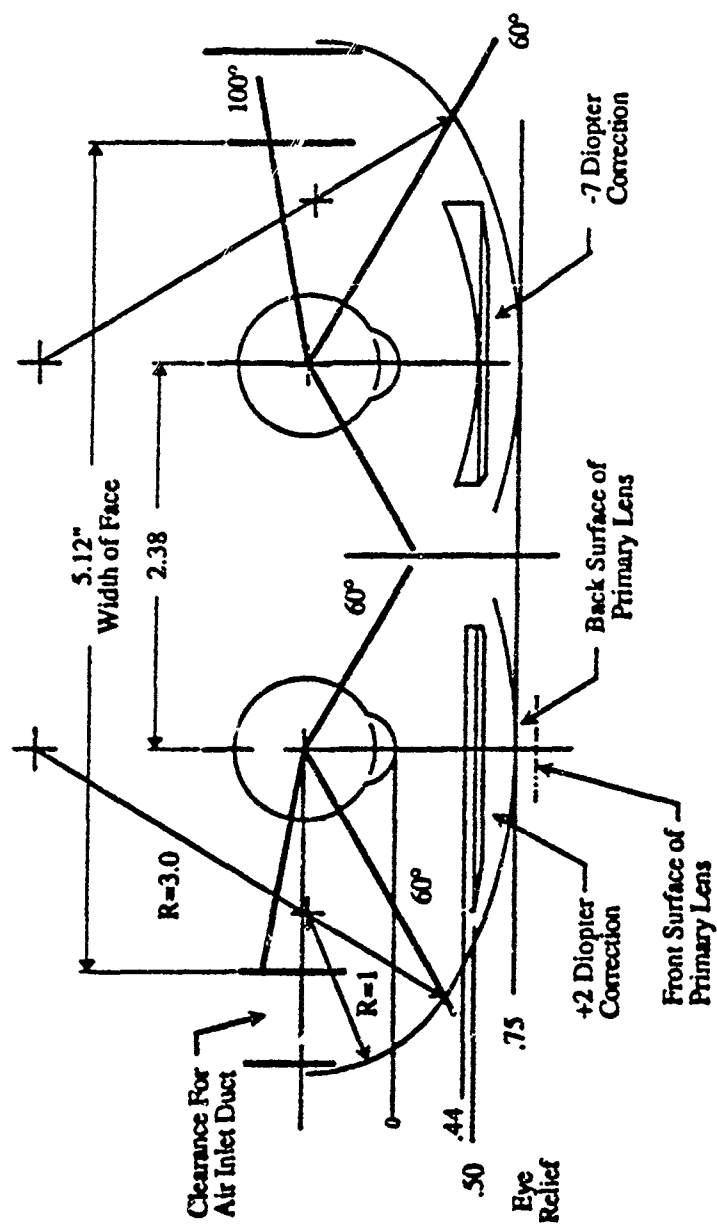


FIGURE 28. THERMOFORMED LENS DESIGN

This improved lens design incorporated into the LPM design as shown in Figure 29. From this drawing, a mold profile and a flat lens pattern were developed (refer to Figure 30). A male thermoforming mold, shown in Figure 31, was then fabricated from aluminum. A polycarbonate plaque was clamped on top of the mold and heated until the plaque conformed to the mold shape. After cooling the resulting lens plaque, flat patterns of the lenses were glued to the plaque and the lenses cut out. Some problems with shaping the plaques and air bubbles were encountered while trying to thermoform the lenses. Details of this process and the experience gained can be found in Appendix E. Some good lenses were completed (refer to Figure 32); however, due to time and cost constraints, a lens holder for these lenses was not finished.

3.4.1.2 Corrective Lens Inserts

Corrective lenses are generally ground from lens blanks having a standard base curve on one surface and the other surface being ground to provide the prescribed correction. The optical correction range initially required for a 1 to 99 percentile population was assumed to be ± 9.00 diopters.(ref 10) To achieve this large range of correction, two or three standard base curves would likely be required.(ref 35) Two base curves were then selected where the front surfaces would have a curvature of $+2.23$ diopters for the minus corrections and $+8.62$ diopters for the plus corrections.(ref 36) To make the various corrections, the back surface of the lens blank would then be ground.

The focal power of a lens curvature is described in terms of diopters which is related to curvature radius by the following equation(ref 33):

$$F = \frac{n-1}{r}$$

Where: F refracting power in diopters
 r radius of curvature (meters)
 n index of refraction of the lens material

The resulting power of a lens consisting of two surface curvatures is determined by the back vertex power (F_v) found by the following relation(ref 33):

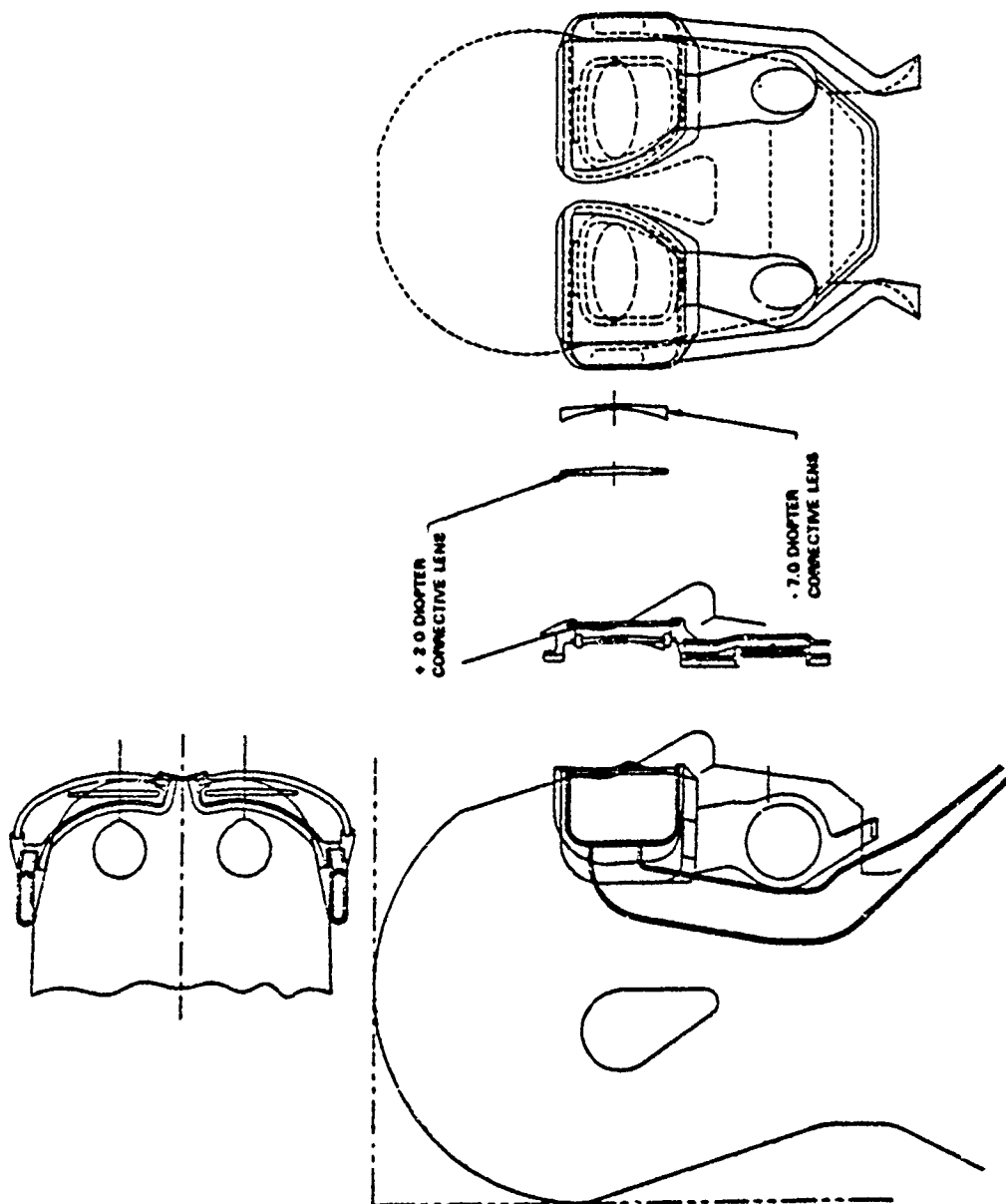


FIGURE 29. THERMOFORMED LENS DESIGN

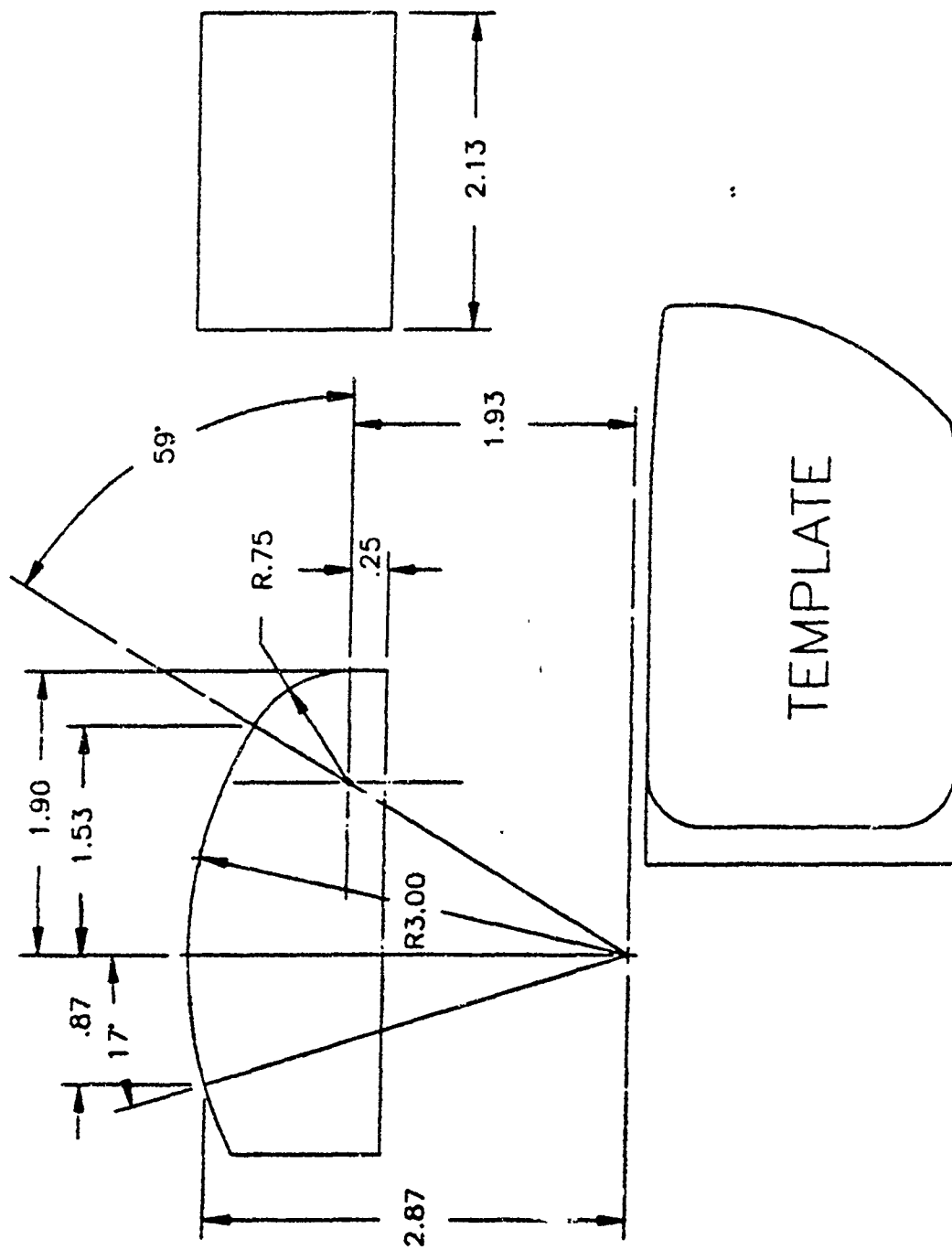


FIGURE 30. THERMOFORMED LENS MOLD DESIGN/PATTERN

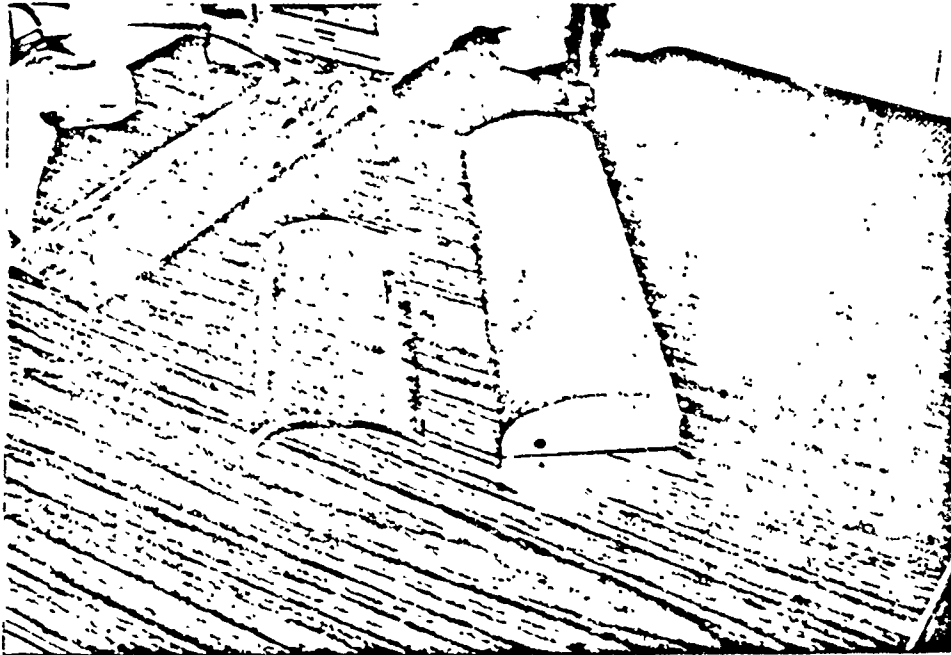


FIGURE 31. THERMOFORMED LENS MOLD

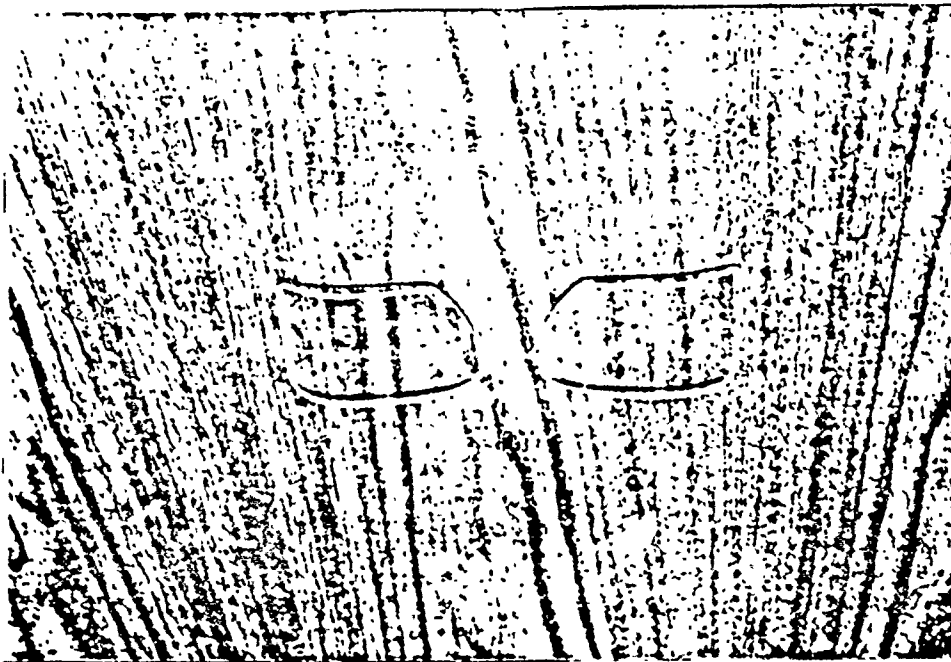


FIGURE 32. THERMOFORMED LENSES

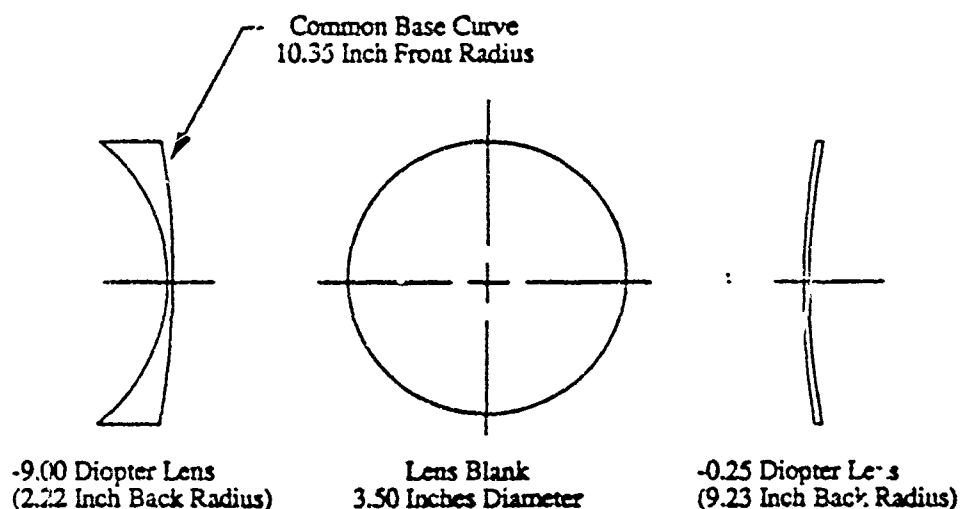
$$F_v = F_1 + F_2 + \frac{F_1^2 t}{n}$$

Where: F1 power of the lens front in diopters
 F2 power of the lens back in diopters
 t lens thickness at the optical center in meters
 n index of refraction of the lens material

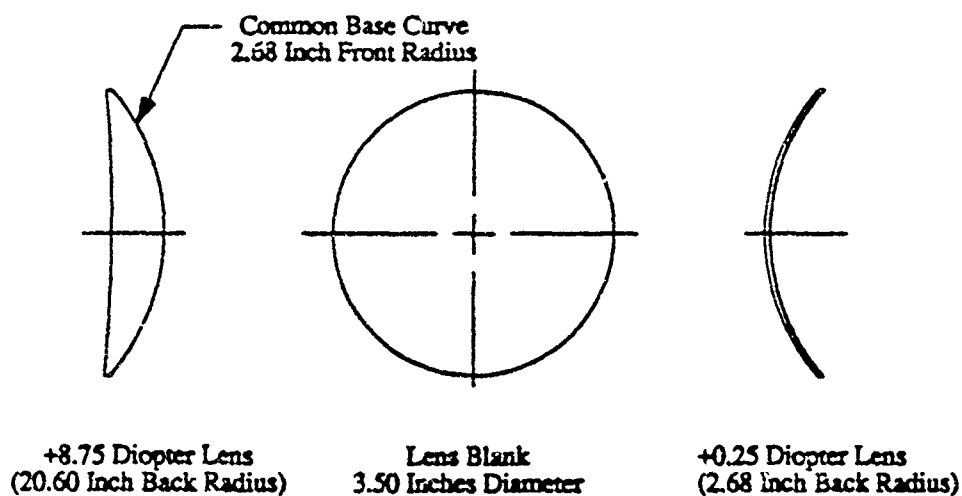
The LPM corrective inserts are made from polycarbonate due to the reasons discussed in the previous section, including light weight, impact resistance, and thinner edge. Because the ballistic protection is provided by the primary lens, the corrective inserts only need to meet the thickness requirements for normal eyewear; the minimum thickness for polycarbonate lenses is 1.5 mm while the minimum for glass lenses is 2.0 mm.(ref 33) Using the above equations and minimum thickness, the shape of the optical correction lenses could be determined where the index of refraction for polycarbonate is 1.586. Drawings of some lens blanks using two base curves are shown in Figure 33 for the corrective range of -9.00 to +2.75 diopters.

The high plus corrective lenses do not easily integrate with the primary lenses due to the differences in radii; the front surface of the high plus lenses and the flat vertical meridian of the primary lenses result in a larger than desired eye relief. The eye relief could be reduced by reducing the size of the optical correction, but this action would also reduce the field of view. The mounting of the high plus lenses could also be difficult since the correction frame insert would have to be attached at the back of the lens which could also negatively impact the eye relief required. A study provided by CRDEC (ref 11) during the course of this program presented new information on the optical correction range requirements. This study was a survey of infantry troops which found that an optical correction range of -7.00 diopters to +1.12 diopters corresponded to the population range of 1 to 99 percentile. This reduced range of correction was then used as the requirement for the LPM.

With the reduced range of optical correction, one base curve was selected which could fulfill the lens requirements. Drawings of the optical correction lenses were made having a +2.23 diopter curvature on the front surface and having a range of -7.64 to +2.18 diopters (refer to Figure 34). This common base curve also makes a common attachment method possible.



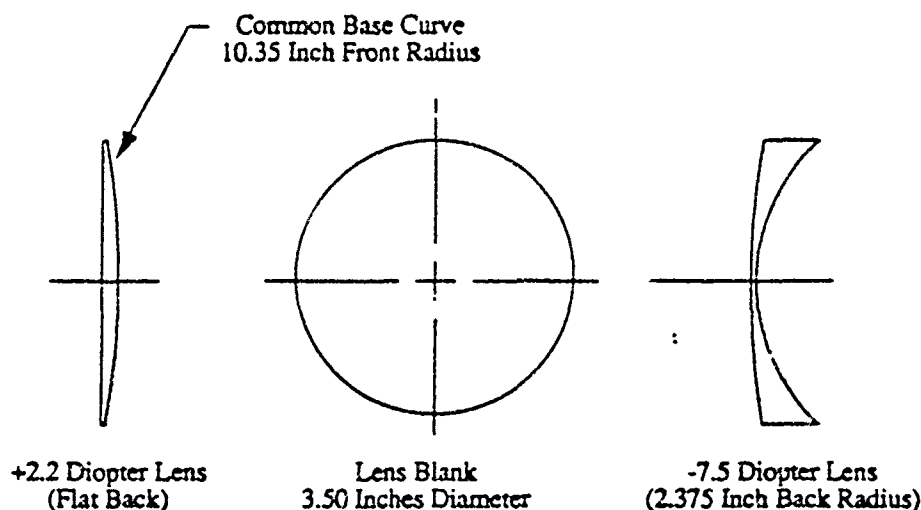
Minus Power Corrective Lens Blank



Plus Power Corrective Lens Blank

Figures Are Drawn For
Polycarbonate Lenses
And In Half Scale

FIGURE 33. OPTICAL CORRECTION LENS BLANKS: ± 9.00 DIOPTERS



Figures Are Drawn For
Polycarbonate Lenses
And In Half Scale

FIGURE 34. OPTICAL CORRECTION: -7.5 TO + 2.2 DIOPTERS

With the optical correction lenses defined, the lens frames needed to be defined and prototyped. Generally, an eyeglass wearer selects a frame and the lens is cut from the lens blank so that the lens shape fits the frame while the optical axis of the lens coincides with the wearer's interpupillary distance (PD). Presently there is no standardization for defining the lens shape; the frame manufacturer supplies lens patterns, called formers, to cut out the lens. (ref 33) To facilitate prototyping, a commercially available lens frame was found which approximated the desired shape of the corrective lenses as presented in Figure 35. Two of these frames were purchased with one frame fitted with +2.00 diopter polycarbonate lenses and the other fitted with -7.50 diopter lenses (refer to Figure 36). One frame was then modified and fitted with mounting tabs to make a male positive for molding corrective lens insert frames. The tab design was used because they could be mounted into matching holes in the flexible lens holder without the use of tools.

The purchased eyewear frame was cut into two lens frames and the excess material ground off. Tabs were cut from plastic having a 0.06-inch thickness. The tab depth (penetration into the lens holder) and length had to be made sufficiently long so that the corrective lens inserts did not fall out or rotate out of alignment during facial movements (the cast frames with corrective lenses installed are presented in Figure 37). These tabs were then attached to the top and bottom of each frame using adhesive. Epoxy adhesive was then used to form fillets at the tab and frame interfaces to

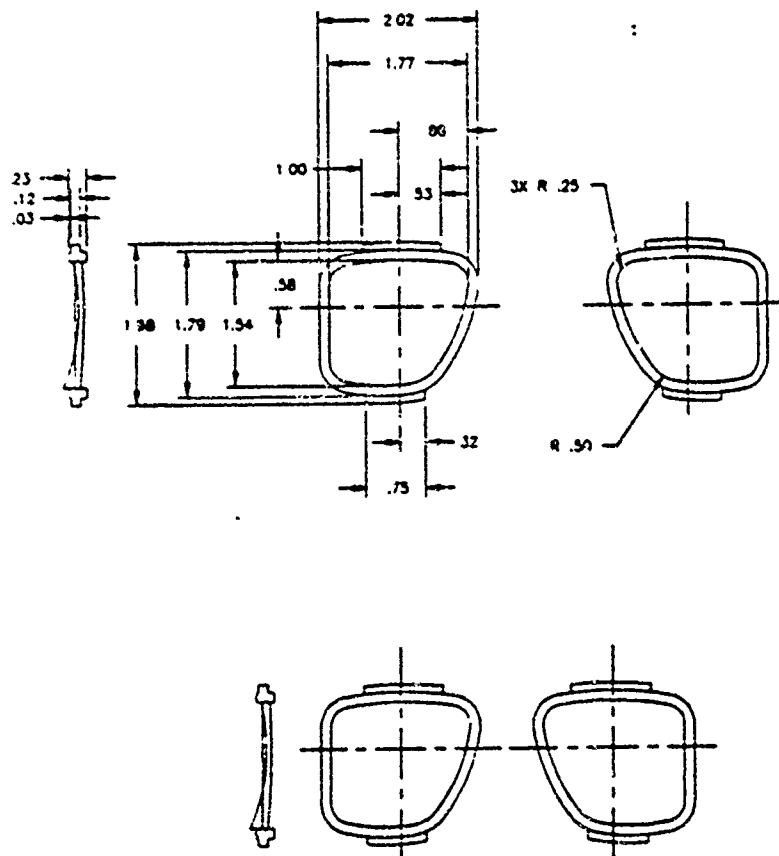


FIGURE 35. CORRECTIVE LENS FRAME FOR THERMOFORMED LENS

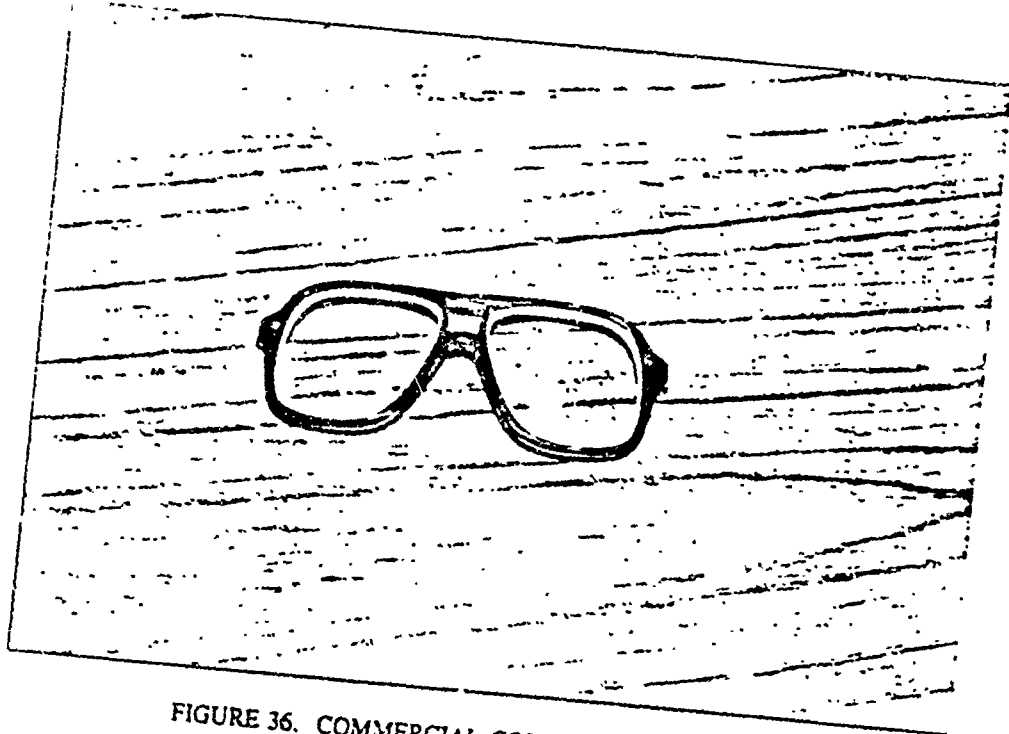


FIGURE 36. COMMERCIAL CORRECTIVE LENS FRAME

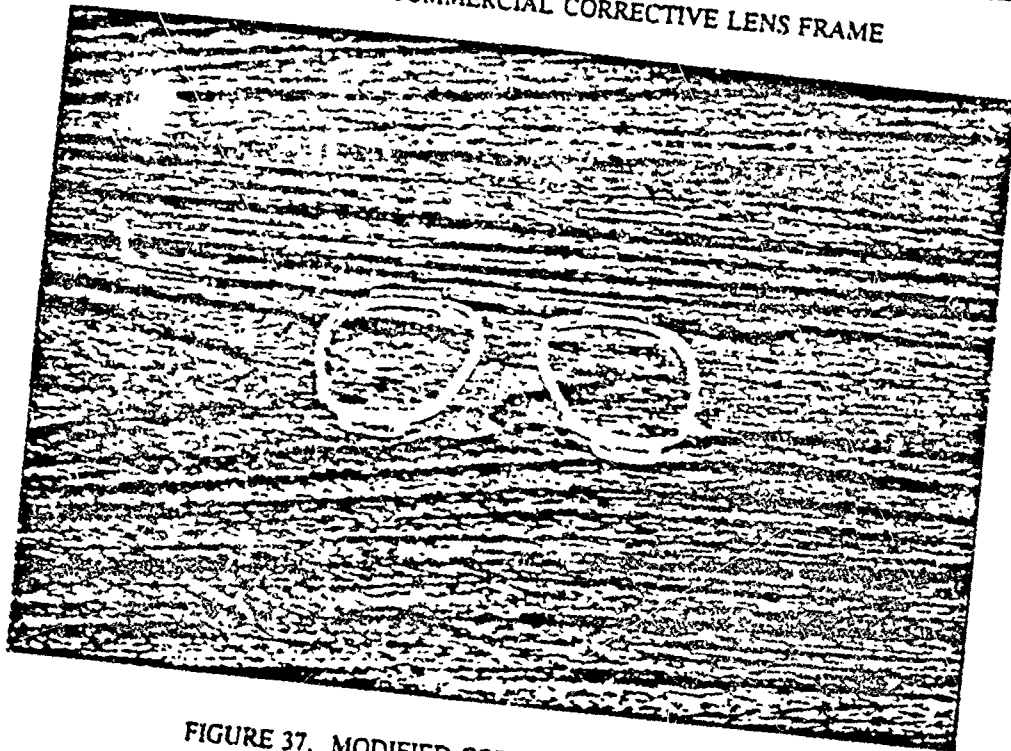


FIGURE 37. MODIFIED CORRECTIVE LENS FRAMES

facilitate demolding. The modified frames, being the male positive, were sprayed with Fluoriglide® (Appendix D, no. 27) parting compound and allowed to dry. HS II RTV® silicone molding compound (Appendix D, no. 16) was used to form the female mold. This silicone is a two-part compound which is relatively easy to work with (24-hour cure time), has higher strengths than some other silicones, provides excellent replication of fine details, and generally does not bond the molded part.

A layer of HS II RTV® was mixed and poured into the bottom of plastic box. The silicone was used because of its flexibility in case undercuts were formed in the mold. The plastic box which was rectangular in shape provided the containment for the mold, both during the mold fabrication and during the pouring of the final parts. The rectangular shape of the plastic box provided a means of registering the two halves of silicone. The male positives (i.e., the modified lens frames) were fitted with the purchased optical correction lenses and were sprayed with silicone parting compound. These male positives were then laid on top of the poured silicone, taking care that the silicone did not flow over the top of the male positives; otherwise undercuts would have been formed. As the silicone began to thicken, 0.25-inch diameter dowel pins were placed adjacent to the frame tabs in the vertical position. These dowel pins were used to core filling and venting holes into the silicone. The length of the dowel pins were sufficient to extend out the top of the plastic box.

After the silicone was cured, the male positives were removed from the mold and the corrective lenses removed from the male positive. The top layer of the cured silicone was then sprayed with parting compound and the male positives were placed back into the mold. Another batch of HS II RTV® was then mixed and poured on top of the mold assembly until the plastic box was filled to the rim. The corrective lenses from the frames were removed so that the top layer of silicone would replicate the bevel inside the lens frames for mounting the corrective lenses.

After the silicone was cured, the mold was disassembled and the male positives and dowel pin cores removed. The mold interior surfaces were then sprayed with silicone parting compound and the mold reassembled into the plastic box. Holes were drilled into the box lid to correspond to the vent and fill holes. This lid provided compression to the silicone molds so that the cast material would not separate the two halves, yet the compression was not enough to deform the mold. TC 2510 epoxy (Appendix D, no. 10) was then mixed and injected with a syringe into the mold. While filling, the mold was held at a slight angle with the fill hole below the vent hole. This action resulted in the epoxy filling the mold cavity from the bottom, thus displacing the air up and out through the vent hole. When making the mold, the male positives were oriented so that the longer

base of the cavity was at the bottom of the mold during filling to eliminate high spots in the mold which could trap air bubbles. After the injected epoxy was flowing from the vent hole, silicone grease was placed over the fill hole as a plug to keep the epoxy from running back out, since this was a low spot in the mold. The filled mold assembly was allowed to set while the epoxy cured. After demolding, the epoxy in the fill and vent holes was removed along with the flashing.

In the first mold attempt, a silicone parting spray was used between the two silicon layers without success; the mold had to be carefully cut apart. Although the resulting mold was not a quality mold, the flexibility of the silicone was forgiving enough that the mold was still functional.

One method to reduce the size of the optical correction insert without reducing the corrective lens is to use a split frame design. A frame, similar to that cast, could be used where the frame not adjacent to the mounting tabs would be removed (i.e., a non-continuous frame). A fixture could be used to locate the frame tabs to the lens while bonding with an adhesive or integral casting the frame tabs to the lens. This design was not pursued during this development phase, but could be implemented at a later stage.

3.4.1.3 Laser Protection Outserts

The laser protection outserts were to be based on the B/LPS laser protection lens. The lens material would be polycarbonate. Because the primary lens would provide ballistic protection, the laser protection outsert only needs to be thick enough for common handling which is about 1.5 mm (0.06 inches). The lens profile would parallel the primary lens to minimize visual distortion. This lens would also be mounted with the primary lens in a common lens holder. However, difficulties were encountered when sculpting the small thickness desired to mount the laser protection lens. This fact, combined with the time considerations involved, resulted in the decision to not include the laser protection outsert into the primary lens holder. The laser protection outsert could be mounted into a separate lens holder having an independent suspension. Again, due to time restraints, the laser protection lens and lens holder assembly were not prototyped.

3.4.1.4 Lens Holder

The lens holder provides a suspension for the primary lens, optical correction inserts, and the laser protection outserts while providing the proper standoff from the eyes. The lens holder

must also accommodate interfaces with the air management components so that dry, inhalation air passes by the lenses for defogging purposes. Making the lens holder from an elastic material would allow the lens holder to fold at the nasal bridge to facilitate stowing.

The primary lens would mount into the lens holder by fitting into a U-shaped channel molded into the lens holder (refer to Figure 38). This channel would run continuously around the lens perimeter and provide a good, tight fit on the lens. The primary lens could be bonded into the channel with a sealing adhesive to prevent chemical agent from penetrating by capillary action or during flexing of the lens holder. The sealing adhesive would not allow removal of the lens during normal use, but it is very lightweight and has a low profile when compared to a mechanical mounting system. The adhesive could be removed at the depot level if the LPM is to be refurbished for a longer service life.

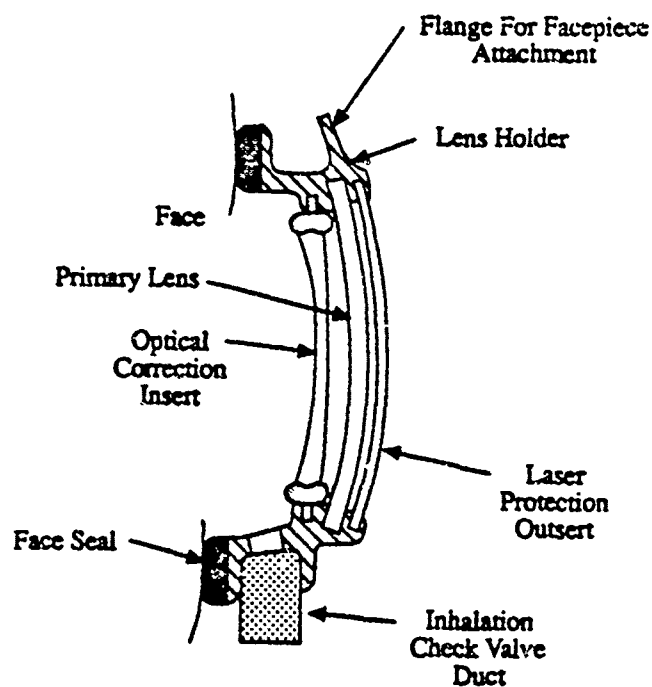


FIGURE 38. LENS MOUNTING DESIGN

The laser protection outsert would fit into a U-shaped channel similar to that used for the primary lens, except that the channel would be discontinued at the outer side of the lens. This channel attachment precludes the use of tools for installing/removing the lenses and can be performed by the wearer during LPM use. By leaving the outer side open, a "handle" can be provided for gripping the lens during installation/removal which would not significantly degrade the wearer's field of view. Mounting the outsert lens directly to the lens holder eliminates the need for an additional lens suspension and the accompanying weight and volume. The small flange between the primary and outsert lenses caused by using a U-shaped channel mounting provides a small standoff which prevents the two lenses from scratching each other.

The optical correction inserts would be mounted to the lens holder like the other two lenses, except that the U-shaped channel would not be continuous. The tabs protruding from the top and bottom of the insert frames would be inserted into matching holes. The depth and length of the tabs need to be sufficient to prevent the inserts from falling out or misaligning during facial movements. Continuous channels were not used for mounting since the material thickness of the lens holder covering the nasal bridge must be minimized to minimize the spacing between the primary lenses.

Flanges would be placed along the perimeter of the lens holder for attaching the facepiece to the lens holder. This flange allows compression of the lens holder to the facepiece material which would be needed for a heat seal or an adhesive joint. For added strength to the lens holder, the flange was located opposite of the primary lens to increase the material thickness at this location. This increased material thickness also would provide greater permeation resistance to chemical agents. The flange would be in the same plane as the primary lens except at the nose bridge since the primary lens is closer to the face. The flange would likely go above the lens plane and merge with the other lens flange of the other eye. All of the flange transitions should be smooth for a better seal with the facepiece.

The air inlet ducts and the inhalation check valve ducts would be attached to the lens holder to completely seal the inhalation air. The lens holder could be formed to surround the duct to provide more surface area for an adhesive joint and to provide a better seal than a butt joint. The transition of the lens holder to the ducts should be tapered so that the facepiece will properly seal at the lens holder/duct interface.

The lens holder seals each eye separately. The seal could be made by incorporating lips into the lens holder or by closed-cell foam attached to the bottom of the lens holder. The foam seal

design was selected over the lip design because it was felt more compliant to fit over a wider range of people, would be more forgiving to seal during facial movements, and would exert less pressure on the face. The minimal clearance between the primary lens and the nose does not provide very much room for a lip seal design and the length of the lens holder covering the nose was minimized to provide a better fit for various people.

Based on the above design approaches, a layout drawing was made of the lens holder and the interface with the air management components (refer to Figures 39 and 40). Laser protection outserts were not included because it was decided to not incorporate these lenses to reduce the time required to produce actual parts for evaluation. It was felt that separate laser protection outserts could be mounted in a separate lens holder at a later time or to incorporate them into the lens holder during a later prototype iteration. Dimensions of the positions of the lenses were provided to the artist for lens holder sculpting. Preliminary sculpting of the lens holder was completed with soft clay to provide a three dimensional model in a timely fashion (refer to Figure 41). Some details of the lens holder, such as the facepiece attachment flanges, were not represented in this preliminary sculpting because the clay used wasn't stiff enough to form these thin parts. All of the details would be added to the final sculpting for molding.

The final sculpting was produced from Chevot Clay® (Appendix D, no. 11) due to its high stiffness and strength. This clay is a clay and wax composition which can be melted (approximately 200° F) and sculpted to produce fine details. Before the lens holder could be sculpted, a face seal was sculpted since this seal provides the base of the lens holder. As presented in Section 3.4.2.3, the sculpted face seal and headform were cast into a female mold of Hydrostone® (Appendix D, no. 18) reinforced with burlap. A male headform with an integral face seal was then cast from Hydrostone®. The Chevot Clay® was then placed on top of this latter headform and sculpted. Care was taken during sculpting to form a symmetric lens holder about the eyes. The lens holder was completed up to the top surface of the primary lenses allowing easy removal of these lenses. Sculpted inhalation check valve ducts and air inlet ducts were made from Chevot Clay® to define their interfaces with the lens holder. The final sculpting of the lens holder is shown in Figure 42. The openings for these interfaces were cut into the lens holder. Some soft clay was then inserted into the holes so that the eye cavities and the outer female mold half would be separate; otherwise, the urethane lens holder could not be demolded. Short tabs showing the outline of the inserts would be molded into the lens holder and the proper hole cut out of the lens holder after demolding. Cutouts were also placed inside the lens holder for mounting the optical correction inserts. The sides

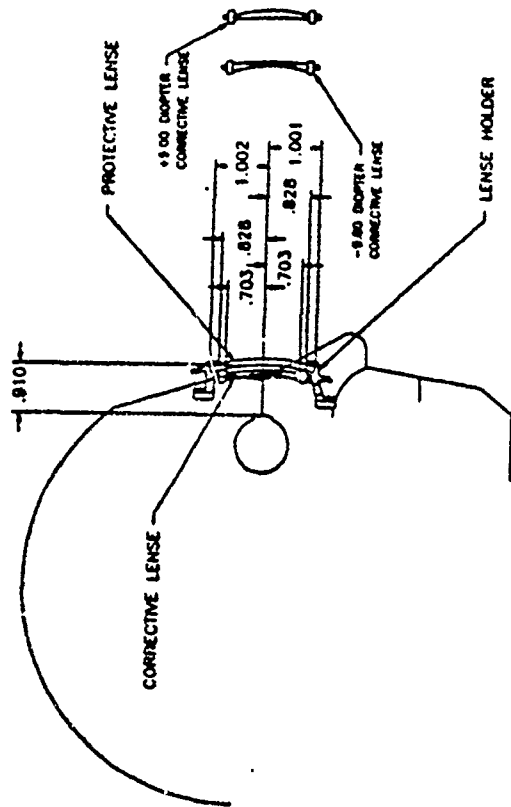
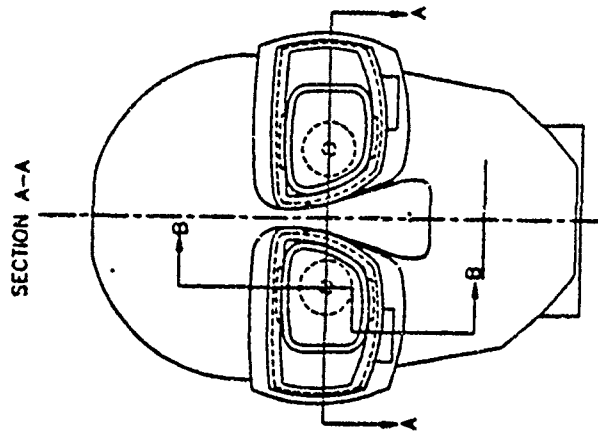
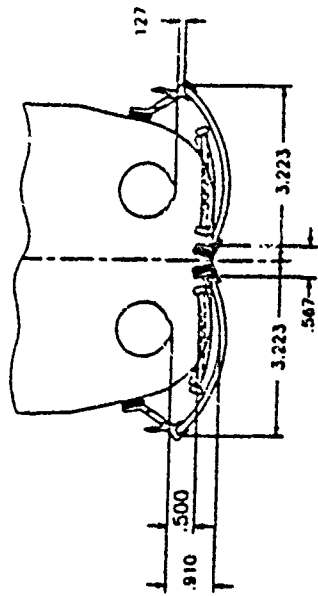


FIGURE 35. B/LPS LENS HOLDER DESIGN

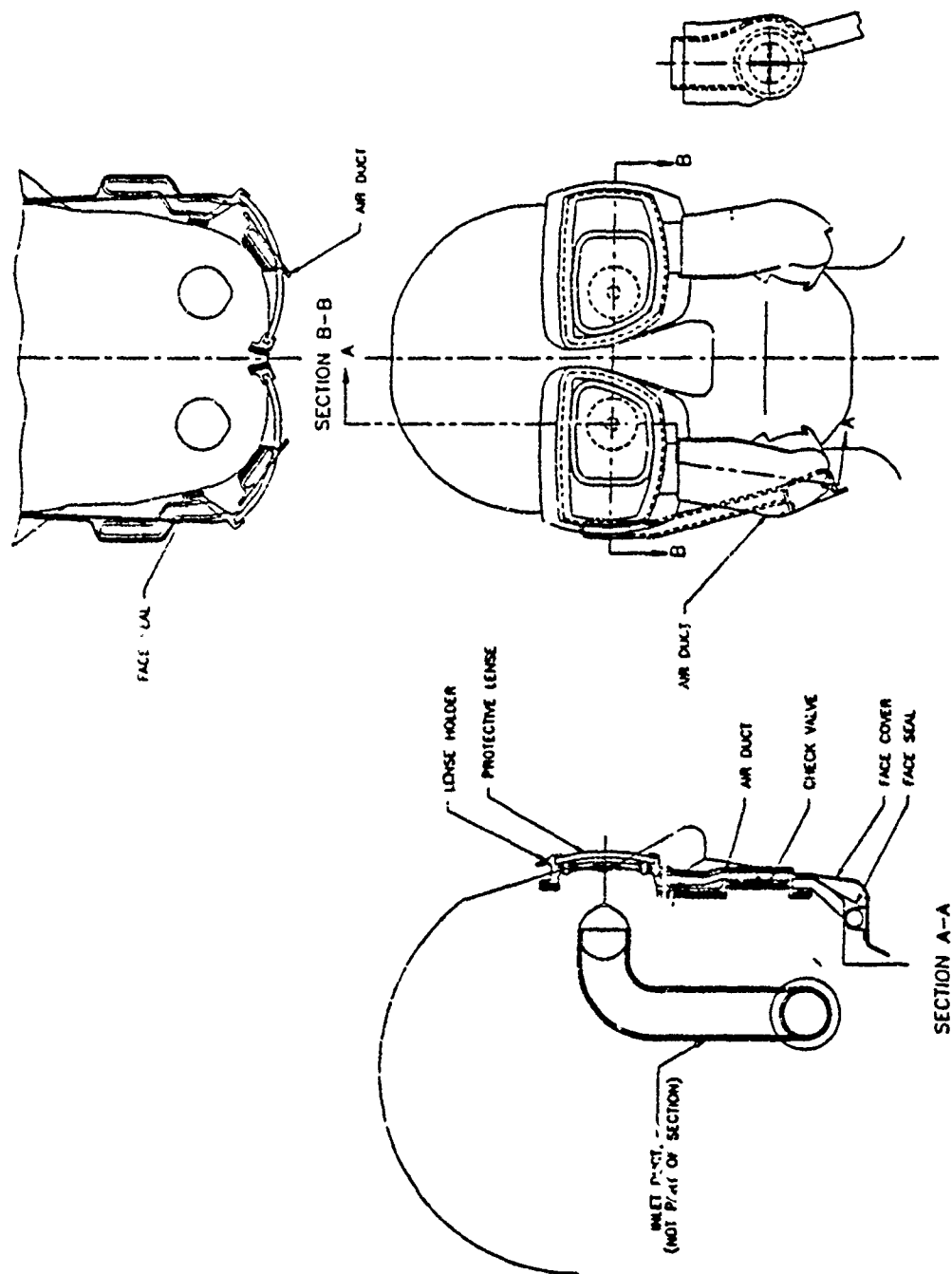


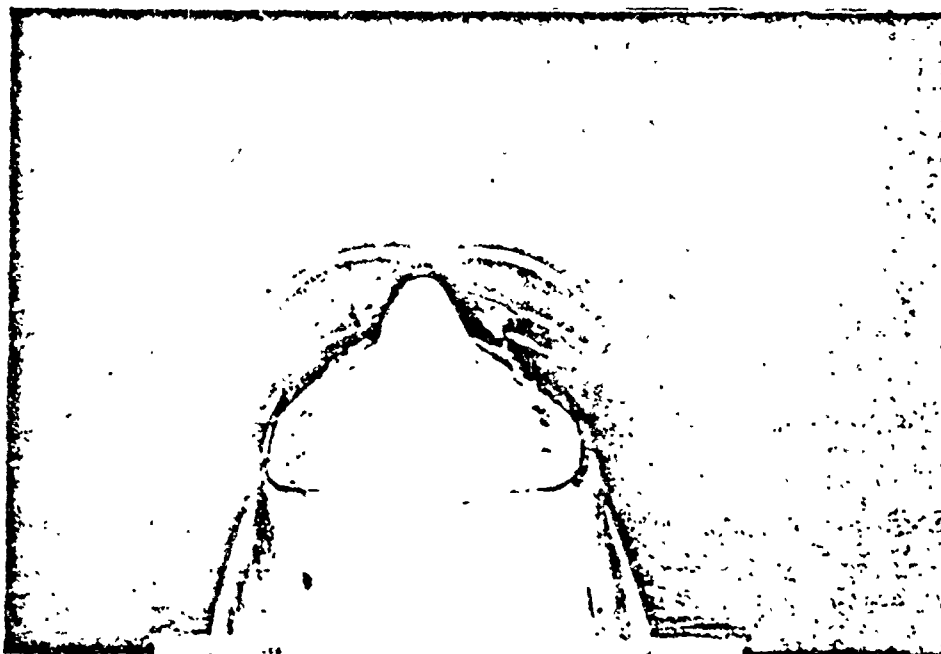
FIGURE 40. PRELIMINARY SCULPTING DESIGN



FIGURE 41. INITIAL COMPONENT SCULPTING

of the lens holder were then smoothed out using a hot-air gun. A top layer was then made to form the cup to mount the primary lenses and to form the facepiece attachment flange. A sheet of clay having a thickness of about 0.06 inches was made and the top layer formed from this sheet. Although the Chevon Clay® provides a relatively high stiffness, it is also relatively brittle due to its wax composition. The facepiece mounting flange could not be formed as desired since the unsupported edges of the top layer kept breaking off. Therefore, the supported flange was made wide enough to attach the facepiece, except in the nose area where only minimal room was available. This approach was taken instead of significantly increasing the top layer thickness which would negatively impact the field of view. The top flange was attached to the lens holder base with the hot-air gun which was also used to complete the final smoothing.

Before the female mold could be made of the lens holder, some preparations had to be completed. Some 0.25-inch diameter holes were drilled into the Hydrostone® head to install some registration pins: one pin was placed above the nose, one below the mouth, and one in each eye. A layer of parting compound consisting of bees wax and toluene was applied to the clay lens holder and the headform and allowed to dry. Two more layers were applied in the same manner. Some metal-filled epoxy (Appendix D, no. 20) was then mixed up. A thin layer of epoxy was brushed inside the



TOP



BOTTOM

FIGURE 42. LENS HOLDER SCULPTING

eye cavities and allowed to cure. Successive layers of increasing thickness were then applied and cured until the lens cavity cores were completed. Two dowel pins were cast into the top layers of each lens cavity core to positively register the cores to the top female mold half. Three successive layers of parting compound were then applied to the tops of the lens cavity cores. Like the lens cavity cores, the outer female mold was generated in layers. A clay dam was first formed to contain the epoxy. The first several layers were thin to replicate the sculpting details. The latter layers were relatively thick and reinforced with fiberglass cloth. The outer female mold half, as shown in Figure 43, was made relatively thick for strength purposes. Once the epoxy was cured, the mold was disassembled.

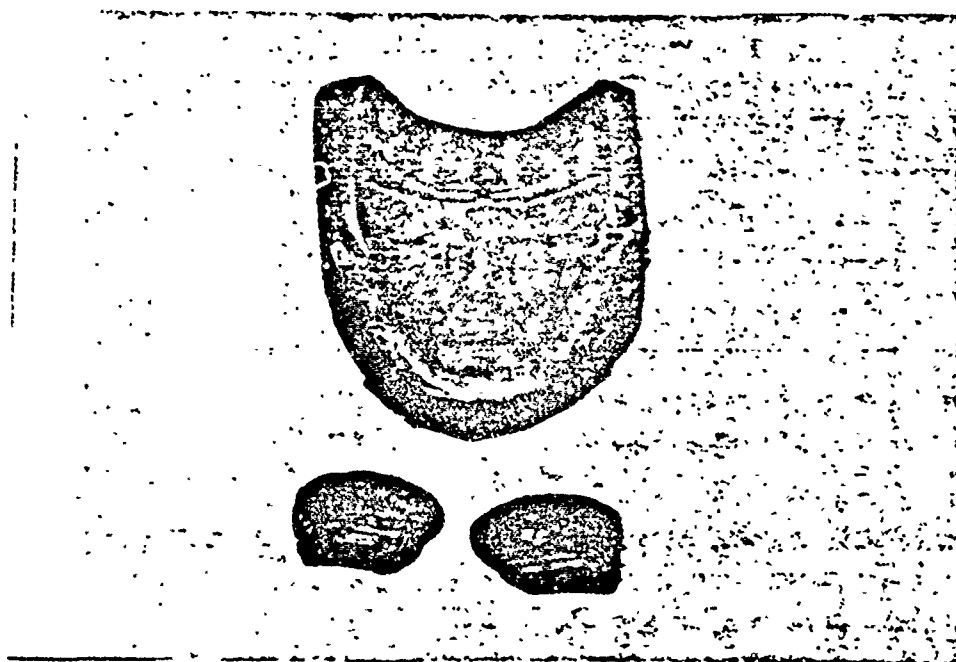


FIGURE 43. EPOXY LENS HOLDER MOLD: FEMALE HALF AND EYE CAVITIES

However, the facial surface of the Hydrostone® male headform separated from the headform. This surface broke into numerous pieces and included the eyes, nose, cheeks, and mouth. The damage could have resulted due to the drilling of the registration pins since the perimeter of the separation was coincident with these holes. Although the separated layer was thin, the male mold half was not usable for casting lens holders. The other mold pieces were successful and the clay was removed. A new male headform with an integral face seal was then made from epoxy to complete the lens holder mold.

The original headform having the face seal sculpted onto it was used to cast a female Hydrostone® mold half for the face seal. As will be discussed in Section 3.4.2.3, this female mold half was broken during casting of urethane foam face seals. An epoxy female and male face seal mold was then cast from this broken female mold which had an intact face seal cavity. The epoxy female mold half having the face seal cavity was used to cast a metal-filled epoxy male headform with a positive face seal. The procedures for casting were the same as that for the lens holder mold. Parting compound was applied to the female mold and buffed after drying. Two more layers were applied in the same manner and a silicone parting spray applied. Thin layers of epoxy were first applied for replication. Thicker layers were then applied for strength. Because of the method of making the female epoxy mold, some undercuts were present which made demolding very hard. The female epoxy mold broke into about 15 pieces which would not be practical to repair. In hindsight, the female mold should have been heavily reinforced prior to casting the matching male half.

However, the resulting male headform was usable and cleaned up. As this male headform was assembled with the other lens holder mold pieces, it was evident that the male headform did not properly fit. It was not clear if the improper fit was due to the method of making molds from molds or if shrinkage of the epoxy caused the female mold to have a smaller curvature since this mold was not heavily reinforced. Parts of the male headform which were believed to be causing interference were ground off and polished, although the final fit was still not good.

Unlike the male headform cast from the epoxy female face seal mold, the lens holder female mold fit properly with the epoxy male face seal mold. As mentioned above, this implies that the curvature of the epoxy female face seal mold changed due to shrinkage. Because of the better fit, a lens holder was cast using the epoxy male face seal mold. However, this mold has a negative face cavity to cast complete face seals. To form a positive face seal, a urethane foam face seal was placed into the negative face seal cavity. A fill hole was drilled into the epoxy female lens holder at the top of the lens holder, above the nose bridge, and perpendicular to the face. This fill hole would vent the

air displaced during urethane pouring. The cast urethane fill hole would also be easy to trim away without effecting the surface to be joined to the facepiece. Silicone parting compound was applied to all of the mold surfaces, but not to the urethane foam face seal. The urethane lens holder was to be cast directly to the face seal. Urethane, TC 960 (Appendix D, no. 7), was mixed and devacuumed while in the mixing pot. It was then poured into the mold and allowed to cure. The urethane foam face seal helped to seal the assembled mold, thus preventing the poured urethane from leaking. After curing, the headform was easily removed from the mold, but the cast urethane could not be removed. Previous casting of the urethane with the silicone spray parting compound was successful on polycarbonate and aluminum, but the urethane adhered to the female epoxy mold. The urethane did not adhere to the epoxy male mold, or for the most part, the epoxy eye cavities. To remove the urethane, it was soaked in acetone and cut out in small pieces. The acetone greatly reduced the strength of the urethane without effecting the strength of the metal-filled epoxy. Demolding was also not helped by the amount of undercuts present in the mold and by the fact that the eye cavity cores could not be pushed out of the female mold half. Relatively large air bubbles were present in the top inside of each primary lens cup due to the curvature of the lenses; otherwise, the cast urethane was basically free from trapped air. In addition, insert casting the urethane foam face seal with the lens holder was unsuccessful because the cast urethane was absorbed into the urethane foam.

Some mold modifications and a new parting compound were used in the second lens holder casting attempt. The fill hole was enlarged to about a 0.75-inch diameter. Vent holes having a diameter of about 0.50 inches was drilled parallel to the fill hole above the location of the trapped air bubbles. Two holes were drilled through the epoxy female mold half so that the eye cavity cores could be pushed out. These holes were located between the two registration pins located in each eye cavity core. The registration pins were also cut shorter to facilitate demolding without losing the registration (the pins were not exactly parallel which caused binding). A new parting compound for epoxy systems, Epoxy Parfilm (Appendix D, no. 12), was also used. The epoxy headform cast from the epoxy female face seal mold was used even though it did not have a good fit, since it provided a positive face seal. Each mold part was coated three times with parting compound as the mold was assembled. Soft clay was rolled into a long gasket and placed around the periphery of the female mold. This clay filled in the open cavities left by the improper mold fit to prevent the poured urethane from leaking. Urethane TC 960 was mixed and devacuumed while in the mixing pot. The mold was elevated about 30" to allow the air bubbles to vent. The urethane was then poured and allowed to cure. Demolding proceeded smoothly by removing the male headform and slowly pushing

the eye cavity cores out with a hydraulic press. The lens holder was then completely removed by cutting through the urethane fill and vent holes. This mold combination resulted in thick flashing which was expected. The extra flashing was removed as much as possible and the duct interface holes cut out. Some small air bubbles were present, but they were mostly insignificant. The most negative aspects of the resulting lens holder was the extra material produced by the improper mold fit. The nose bridge area and the part in contact with the forehead are the most noticeable which also hinder folding of the lens holder. The increased weight and bulk are also undesirable.

Because the epoxy male face seal mold does provide a good fit with the lens holder mold, this headform was used in the next casting attempt. To form a positive face seal from the negative face seal cavity, a urethane foam face seal was used. To preclude this foam from absorbing the cast urethane, the urethane foam was coated with a thin layer of TC 960 urethane and inserted into the male face seal mold. Epoxy Parfilm was heavily applied to all of the mold pieces mold during assembly. TC 960 urethane was mixed, degassed in the mixing pot, and poured into the mold. The resulting casting was properly formed by the male face seal mold and urethane foam face seal (refer to Figure 44). This method was used to cast the remaining prototype lens holders.

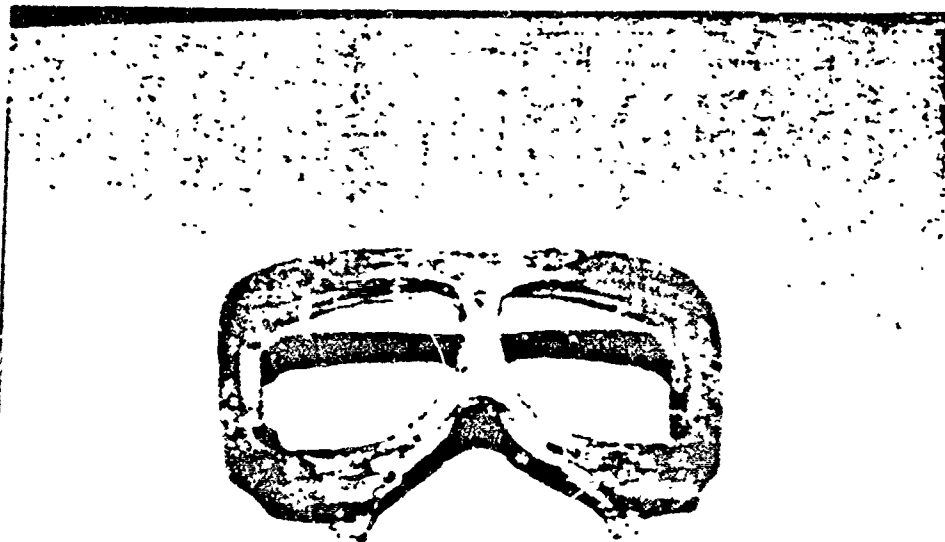


FIGURE 44. CAST URETHANE LENS HOLDER

3.4.2 Air Management Components

The air management components direct the clean air from the filter assembly to the nosecup area via the lens holder and passes exhaled air from the nosecup to the ambient air. These components must seal the face area from potentially contaminated air coming up under the hood, prevent moist exhaled air from entering the lens cavity to prevent fogging and a buildup of CO_2 , and prevent potentially contaminated outside air from entering the face area through the exhaust check valve. The basic approach in designing the air management components is to seal the minimum amount of area to reduce the size of the seals and to integrate the seals with the other parts to result in multifunctional parts, again to reduce attachments and the overall size. As shown in Figure 40, the air management components include the air inlet ducts, the inhalation check valve assembly, the chin seal, the face seal, and the exhaust check valve assembly. The lens holder also helps the proper transfer and sealing of air, but it is described under the lens system. After each of the components was initially designed, they were rough sculpted on a headform as a three dimensional model to provide a better feel of the design. This rough sculpting is shown in Figure 41. Molds were then machined from aluminum to form representative parts for evaluation. The machined molds were also used to cast clay parts which could then be formed to the face, thus resulting in a more symmetrical design and assisting the sculpting process. After forming the clay parts to the face, molds were made, cores were made, and the final parts cast.

3.4.2.1 Inhalation Check Valve Assembly

Two inhalation check valve assemblies transfer air for inhalation from the lens holder to the nosecup area. As discussed in Section 3.3.2.2, C23 check valves provided by CRDEC are used in these assemblies to prevent exhaled air from entering the lens cavities. These assemblies are also located close to the mouth to provide a standoff for the mouth area where the exhaust check valve is suspended from the face piece. The bottom surface of the duct area is a seal to prevent leakage into and from the nosecup area. The duct attaches to the lens holder which completes the seal around the nose. The bottom of each check valve assembly interfaces with the chin seal to prevent leakage around the chin. The facepiece is attached to the top of the inhalation check valve assembly to complete the resulting "nosecup".

Based on the duct testing described in Section 3.3.2.1, the desired duct area was to be about 0.20 in² to provide a suitable pressure drop. The cross-sectional area of the duct was rectangular to provide a minimum profile (refer to Figure 45). The check valve was located adjacent to the mouth area to provide sufficient standoff while minimizing the height adjacent to the lenses which could hinder the downward field of view. The top of the check valve housing was made solid to provide a large area for bonding the facepiece to the inhalation check valve assembly. The bottom of the check valve housing was made open, allowing the check valve to be installed and replaced if necessary. The flow of air through the assembly is through the duct to the top of the check valve, down through the check valve, and out the side of the check valve housing. The C23 check valve is mounted to the housing by a lip which is cast into the housing. Angling the check valve was investigated to reduce the footprint and to place the check valve normal to the air flow for less resistance, but the angling only increased the standoff profile which is undesirable.

Lip seals could be placed on the bottom surface of the assembly duct as shown in Figure 46. Two lips provide stability of the part on the face. The lip closest to the nosecup area is turned towards the mouth for stability and to passively seal under exhaled positive pressure. The lip farthest from the mouth is turned out to passively seal against a negative pressure in the nosecup area. The duct is separate from the seal area to provide a higher level of protection in case the lip seals would have some minimal leakage through one lip. The decision was later made to make a single face seal from a flexible foam. The check valve duct would sit directly on top of this foam seal and transfer the suspension force from the facepiece to the foam seal.

Flanges were placed on each side of the duct to provide a bonding area between the inhalation check valve assembly and the facepiece. Pressure could be applied to these flanges to form the bond since applying pressure through the ducts might be difficult.

Because the inhalation duct would experience a negative pressure, the duct would need to be designed to prevent it from collapsing during inhalation. Several methods could be implemented to preclude collapsing: the duct walls could be stiffened which could degrade the fit and foldability, a "spacer" material could be placed inside the duct to provide support, or lips could be molded integral with the duct to reduce unsupported areas.

Presented in Figure 45 are the approximate design of the inhalation check valve assemblies. Female molds of the parts and the cores were machined from aluminum to reflect this design. Dimensioned mold drawings can be found in Appendix C.

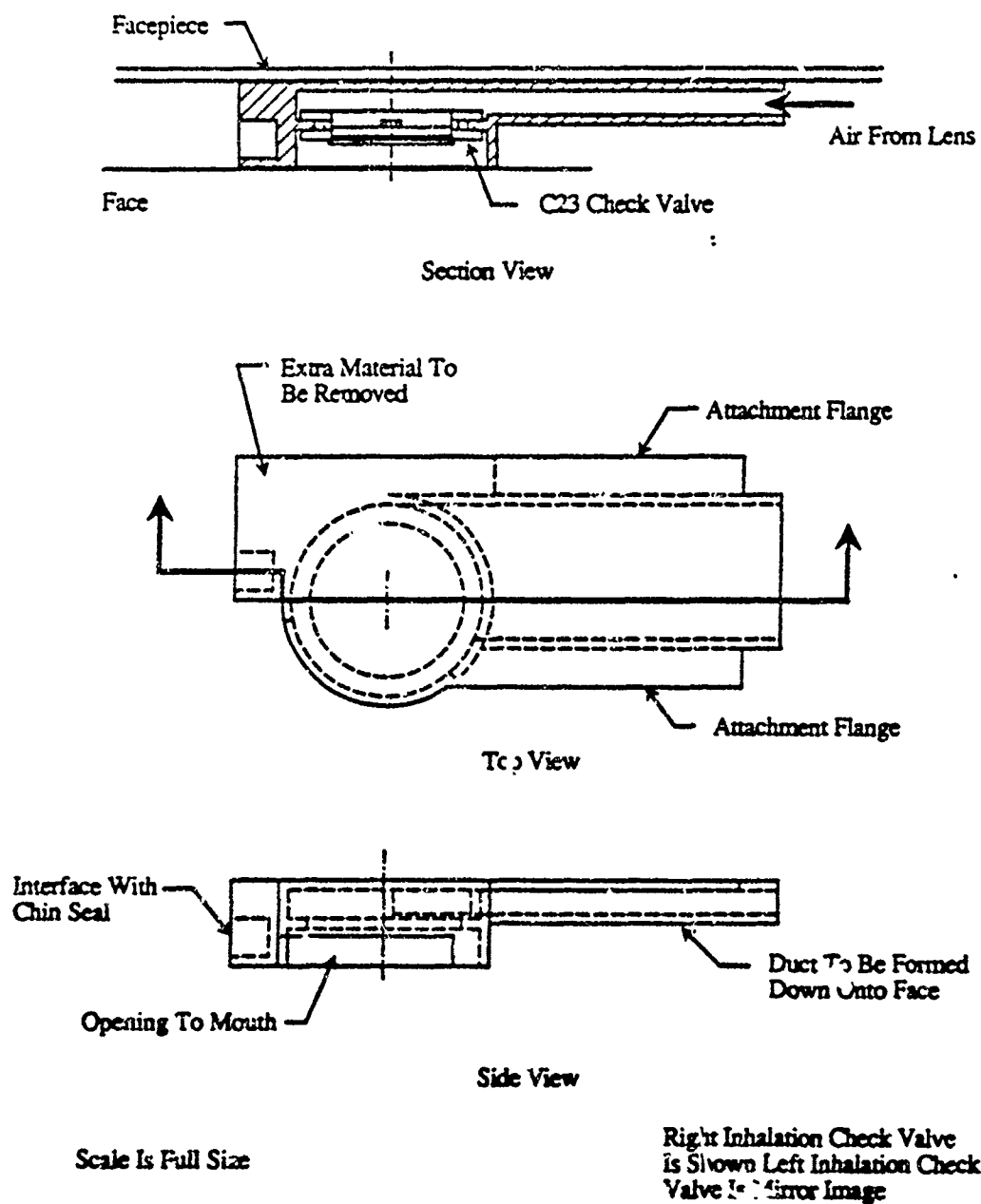


FIGURE 45. INHALATION CHECK VALVE DESIGN

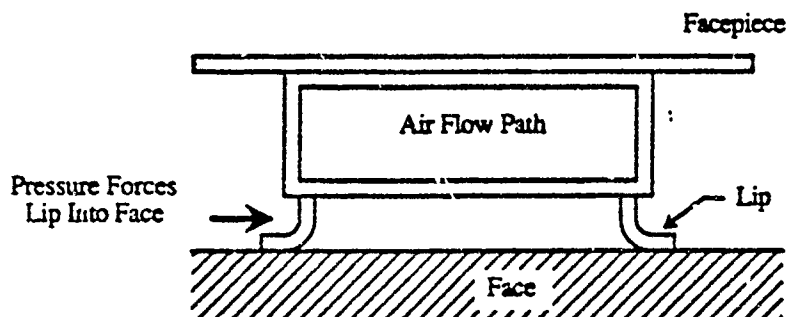


FIGURE 46. INHALATION CHECK VALVE DUCT: LIP-SEAL DESIGN

The female molds were used to form several clay parts of the check valve assemblies. These solid parts were provided to the artist for fitting to the face and integrating the parts together with Chevot Clay® (Appendix D, no. 11).

The first attempt at casting a check valve assembly using the machined molds was made with transparent Sylgard® 184 (Appendix D, no. 14) silicone rubber and paraffin wax cores. The silicone was a room temperature cure material which was important so that the paraffin would not melt prematurely (paraffin wax melts at approximately 130° to 140° F). When making the core for the top of the check valve and air duct, spacer material made from Saran® (Appendix D, no. 22) was imbedded into the paraffin. The 0.25-inch diameter register pin located the cores to the mold at the check valve location, but no method of spacing the top of the check valve core or the air duct core was designed into the mold. Therefore, small squares of neoprene rubber having the proper thickness of 0.06 inches was placed in the mold for this registration. Silicone parting spray (Appendix D, no. 28) was generously applied to the parts in the mold as assembled. Silicone rubber was mixed up and devacuumed before it was poured into the mold. After curing and demolding, it was found that the silicone would not cure adjacent to the neoprene rubber although the rest of the casting cured satisfactorily. The paraffin wax cores were easily melted out of the casting leaving the spacer material

in place. A light film of parafin remained on the silicone and the spacer material, but an attempt to remove it was not made since the uncured silicone around the neoprene made the part useless for evaluation. The cast silicone inhalation check valve assembly and the air inlet duct are shown in Figure 47.

The second molding attempt used urethane, TC 960 (Appendix D, no. 7) for casting the part. Also, the cores were made from Chevot Clay® instead of parafin wax because the clay had a higher stiffness. The parafin was found to be undesirable as a core material due to its flexibility; the cores tended to deform during normal handling which made casting uniform wall thickness difficult. However, making the cores from Chevot Clay® was more difficult than the parafin due to the higher melting temperature. Like the parafin, the Chevot Clay® was melted in a double boiler, but since the melting temperature of the clay is close to the boiling point of water, it took considerably longer to melt the clay. Also, the core molds had to be preheated to about 140° F; otherwise the Chevot Clay® would quickly solidify upon contact with the room-temperature aluminum and form air pockets. The clay cores were allowed to cool before demolding to develop sufficient strength. It was found that placing the poured core molds in the freezer for about 5 minutes immediately before demolding would

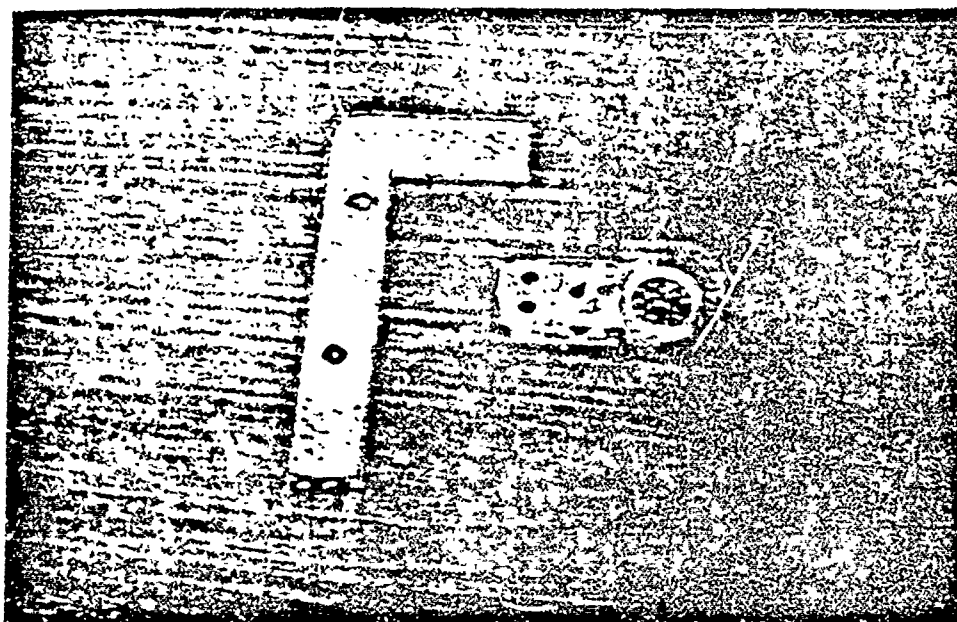


FIGURE 47. SILICONE INHALATION CHECK VALVE ASSY
AND AIR INLET DUCT

help facilitate demolding. To provide support structures to the cast check valve assembly, 0.06-inch diameter holes were placed along the centerline of the duct with a 0.50-inch spacing. These holes were formed with a hot metal rod of the proper diameter. These holes would be filled with urethane during casting to form support columns which would not produce a significant pressure drop during inhalation. Again, to register the duct core properly in the female mold, urethane rubber was previously cast to a 0.06-inch thickness and cut into small squares. These squares were cleaned with alcohol so that they would be cast in-place with the cast urethane. Silicone spray release was generously applied as the mold was assembled except on the urethane spacers. The urethane resin was then mixed and devacuumed for five minutes while in the mixing pot. After pouring urethane into the open-top mold, the mold was devacuumed for several minutes. The mold was then overfilled with urethane and a flat cover was then placed on top of the mold, careful not to introduce air bubbles. After curing and demolding, the castings looked very good. The Chevot Clay® cores worked well, except that the clay could not be easily removed. As the clay was heated, it melted, but it would not flow. A small brush was then used to physically remove the clay. A C23 check valve placed into the check valve assembly fit properly. The air inlet duct and inhalation check valve assembly cast from urethane are presented in Figure 48. These parts were bonded with representative eye cavity and a filter connector for air flow resistance testing.

Clay parts were made from Chevot Clay® using the machined aluminum molds for forming to the face. Although this clay does have good strength and rigidity, the thin attachment flanges were quickly broken off during the forming process. A heat gun was used to soften the clay which could then be pushed down to conform to the handsculpted face seal on the headform. The inhalation ducts were inserted into the air passages of the sculpted lens holder. The inhalation duct formed a positive interface in the lens holder for proper orientation during assembly. The lens holder also had flanges on the top and bottom of the inhalation duct for easier attachment. The final clay inhalation check valve assemblies are shown in Figure 49.

A two-piece female mold was constructed for each inhalation check valve assembly using metal-filled epoxy (Appendix D, no. 20) for strength and durability. The first several layers were applied as thin coats for reproducing the details. Thicker coats could then be applied to speed up the mold-making process. However, the amount of epoxy applied at any one time was limited since a large mass of curing epoxy could generate heat and potentially soften the formed clay positive. The first mold piece was cast with two metal dowel pins for registration pins. The mating mold piece was then cast on top of the first piece, after three layers of bees wax/toluene parting compound were

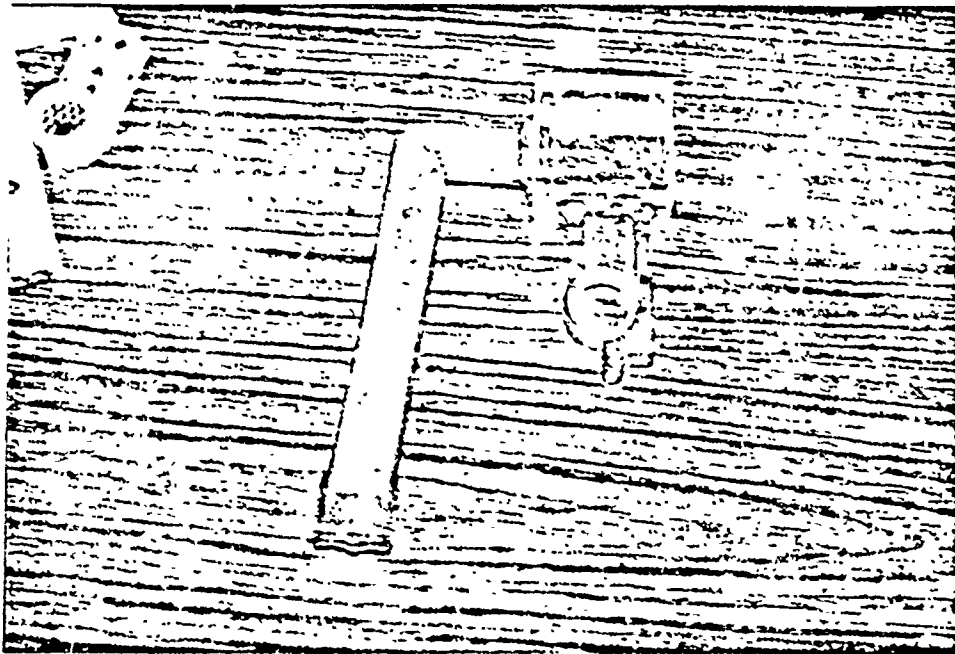


FIGURE 48. URETHANE INHALATION CHECK VALVE ASSY
AND AIR INLET DUCT

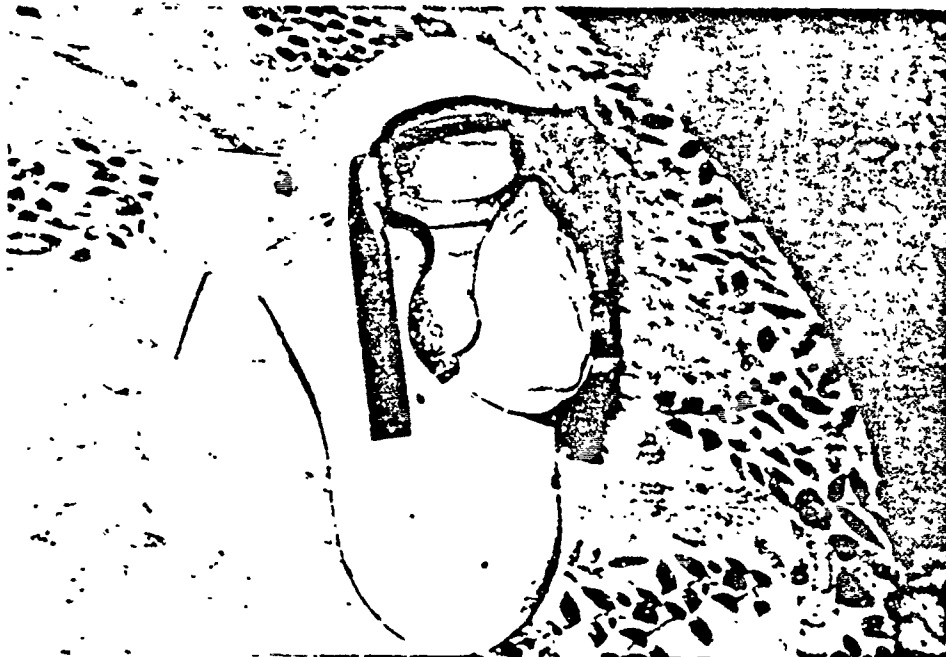


FIGURE 49. SCULPTED AIR MANAGEMENT COMPONENTS

applied. After curing, the molds were separated and the clay positive cleaned out and a single, large fill/vent hole was milled into one half of each mold assembly. The epoxy molds are shown in Figure 50.

Cores of the flow path were made using the female molds of the inhalation check valve assembly. Positive cores of the check valve cavity were cast from polyester resin (Appendix D, no. 4) using the machined aluminum molds. These two solid disks together formed the core for the lip which would be used to mount the C23 check valve seat. These positive cores were placed into the epoxy female inhalation check valve molds using the registration pin. A combination of 0.06-inch thick neoprene rubber sheet and soft clay were used to simulate the desired urethane casting. This clay and rubber lining left a cavity of the desired flow path. The molds were assembled after spraying with Epoxy Parfilm (Appendix D, no. 12) which worked very well on the lens holder mold. Epoxy, TC 2510 (Appendix D, no. 10) was then mixed, devacuumed in the mixing pot, and poured into the mold. This epoxy bonded sufficiently to the polyester resin check valve cavity positive cores to form a single positive core of the inhalation check valve assembly flow path. However, the Epoxy

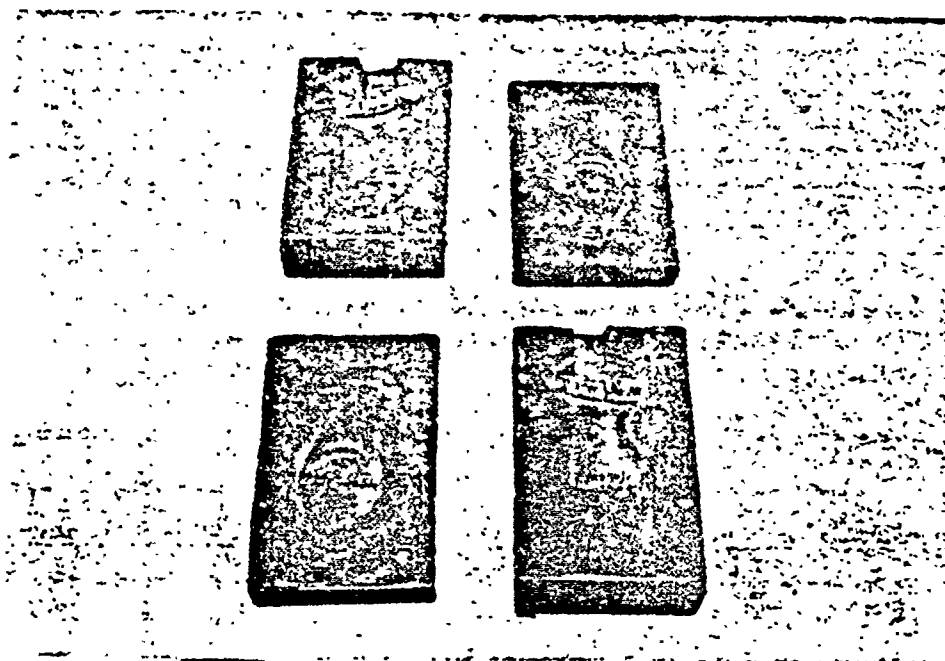


FIGURE 50. EPOXY INHALATION CHECK VALVE ASSEMBLY MOLDS

Parfilm did not prevent the TC 2510 from bonding to the epoxy mold. The cast core was not effected since it was totally encapsulated by the neoprene rubber and soft clay. The epoxy cured in the fill/vent hole had to be ground out for pouring the urethane at a later time.

A female mold was cast from the epoxy flow path core using soft HS II RTV® (Appendix D, no. 16) due to the undercuts of the C23 mounting lip. The silicone was mixed and devacuumed in the mixing cup. A layer of the silicone was then poured into the bottom of a small plastic box and allowed to cure. The plastic box provided structure to the silicone mold and registered the two mold halves together. The cured silicone layer provided a hard layer which kept the epoxy positive core from sinking into the low viscosity silicone. Another batch of silicone was made, the epoxy core placed inside the box, and the silicone poured into the box. The HS II RTV® cures directly to previously cast HS II RTV® to form one piece, even when parting compounds were used to prevent this from occurring. During this mold fabrication, this feature was taken advantage of. After pouring the second layer to the rim of the plastic box, a dam was made from tape around the box rim. A third layer of silicone was then poured. This last layer increased the material thickness about the epoxy core and also provided a handle for removing the silicone mold from the plastic box. After the final curing, the solid silicone female mold was removed from the plastic box. A knife was used to carefully cut the silicone into two pieces and the epoxy core removed. The silicone was cut perpendicular to the C23 check valve mounting lip because a parallel cut could damage this lip. Registering the silicone halves in the plastic box was not a problem. A fill hole was cut into the mold parting surface to the bottom of the check valve core since this location was not to be filled with urethane. A vent hole was cut adjacent to the end of the inhalation duct which was on the opposite end of the cavity core from the fill hole. These hole locations allowed easy removing of the cast clay and were on the mold parting line to allow easy mold disassembly following casting. A Chevot Clay® and parafin wax mixture, approximately even volumes, was melted and poured into the assembled molds. This clay/wax mixture was used since it had the melting temperature of the parafin while it had some of the strength of the Chevot Clay®. After the clay cores were removed, the flash was trimmed away. Holes were then melted into the clay along the longitudinal axis of the inhalation duct with a heated 0.06-inch diameter rod so that urethane support columns would be formed during casting, thus preventing collapsing during inhalation.

Inhalation check valve assemblies were cast from TC 960 urethane using the following procedures. The clay cores were placed into the mold with the registration pin and any alignment corrected. These cores were then removed and the epoxy female inhalation check valve molds were

sprayed with Epoxy Parfilm parting compound. The female mold was then cleaned with alcohol where the clay core comes into contact with it. This contact area was then heated using a hot, hollow cylinder which fit over the core registration pin. The clay core was then placed onto the registration pin and held into the proper orientation. The heated epoxy would cause the contact surface of the clay to slightly melt and then harden, bonding the clay core into position. This method of registering the clay core eliminated the need to place small spacers of urethane in the mold to be cast in place (which when used to cast urethane in the machined molds did not always result in good bonding). The mold was then assembled. Urethane was mixed, devacuumed, and poured into the mold. After the urethane was half cured, heating the mold to about 120°F for about 2 hours accelerated the curing rate and also significantly softened the clay core. Immediately after removing the mold from the oven, the mold was disassembled and the clay removed while it was still soft. The flashing was then removed from the cast part and the part cleaned with alcohol.

3.4.2.2 Air Inlet Ducts

The air inlet ducts transfer clean air from the filter assembly to the lenses. Because the filter assembly is to be replaceable, connectors must be present allowing the air inlet ducts to be connected and disconnected from the filter assembly. This connection was initially assumed to be a female fitting on the lens side of the duct which attaches to the hood (refer to Figures 51 and 40). However, the preliminary development of the duct assumed that any fitting to the filter would be designed as part of the filter itself and would have to accommodate the air inlet duct. The other end of the air inlet duct would be joined to the lens holder by bonding with adhesive.

The air inlet duct was designed with a cross-sectional area of 0.20 in² based on the pressure drop testing presented in Section 3.3.2.1. To keep the profile low, the cross-section of the duct was taken to be rectangular (refer to Figure 51). The duct wall thickness is 0.06 inches so that weight is kept to a minimum while providing flexibility. The casting material is urethane because of its strength, flexibility, and the ease of bonding it to other materials. Another aspect of the air inlet duct design which is important is the duct routing through the hood. The duct attaches to the outer side of the lens and makes a bend to go down the side of the face. The duct must not interfere with any earmuffs which could be worn at the same time, but a sharp bend radius will cause some air flow resistance. The helmet chin strap forms a triangle between the ears and the chin with clearance between the face and chin strap where the air inlet duct can pass through without being compressed.

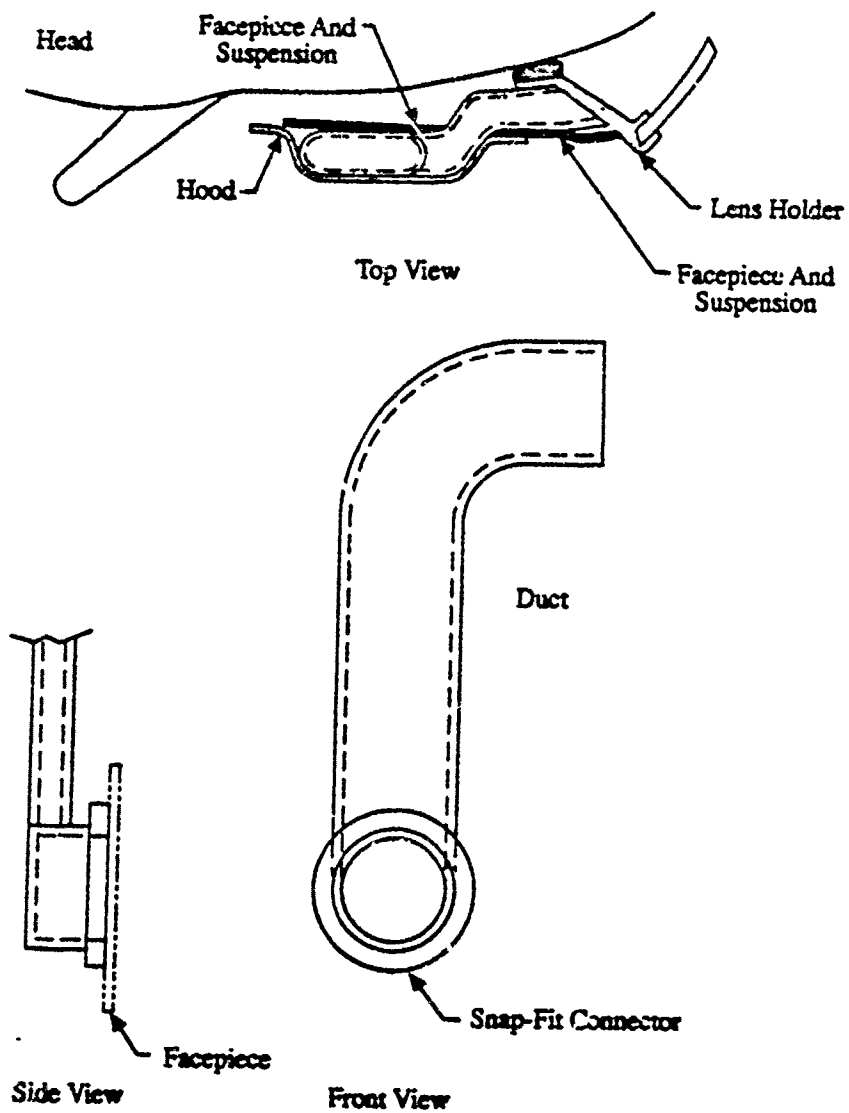


FIGURE 51. AIR INLET DUCT DESIGN

The air inlet duct must not interfere with the seal between the face and the face seal. This seal is caused by the suspension pulling on the facepiece, which in turn forces the face seal onto the face (the force is transferred from the facepiece to the face seal via the lens holder, inhalation check valve assemblies, and the chin seal). Therefore, the air inlet duct should not contact both the face and the facepiece (or suspension) or it could reduce the force applied to the face seal. The profile of the air inlet duct was made lower than the height of the other facial parts to keep this effect from occurring. In addition, the air inlet duct should pass through the facepiece and down towards the filter assembly so that the facepiece and suspension will be in direct contact with the head.

Aluminum molds were machined to form representative air inlet ducts. Like the inhalation check valve assembly, representative parts and clay parts for sculpting the final parts were cast from these molds. The molds were designed for ease of fabrication. For example, the end of the duct is a semi-circular shape; the end of the cast parts were trimmed as needed. The molds for the duct and the duct core were integrated into one mold. Dimensioned drawings of these molds can be found in Appendix C.

The processes used in making clay parts as a baseline for the artist and molding representative parts were the same as that used for the inhalation check valve assemblies. The details of the processes are presented in that section and only a summary of the air inlet duct processes is provided here. Chevot Clay® (Appendix D, no. 11) was used to make clay air inlet ducts for the artist, allowing a sculpting baseline for fitting to the headform. The first molding attempt used Sylgard® 184 silicone rubber (Appendix D, no. 14) as the casting resin with a parafin wax core and neoprene spacers. The mold was assembled and the flat cover clamped to the mold. The assembled mold was placed in a vertical position with the opening in the mold at the highest point. The mold was rotated so that the lower arm of the duct cavity was not horizontal; this action allowed air bubbles to float to the open top of the mold. The silicone did not cure adjacent to the neoprene, but the wax was easily melted out. The cast silicone air inlet duct is shown in Figure 47. The second molding attempt used urethane with a Chevot Clay® core. This core had 0.06-inch diameter holes placed along the centerline with 1.0-inch spacing. After curing, the Chevot Clay® could not be melted out, even after placing the duct in boiling water. Since alcohol helps break up the Chevot Clay®, the duct was allowed to soak in alcohol. However, the alcohol was absorbed by the urethane which caused swelling and a loss of strength. The duct was extensively damaged due to the loss of strength, but the strength was regained as the alcohol desorbed in air. Another casting attempt was made using the same approach, except that the core was made from a mixture of Chevot Clay® and

paraffin wax. This mixture was easier to work because it lowered the melting temperature of the Chevot Clay®, yet it retained most of the stiffness. After the air inlet duct was cast and cured, the core was removed by a freezing and breaking process. First the duct was placed in a freezer to make the core material brittle. Flexing the frozen duct would crack and break the core material without damaging the urethane. The core material would start to warm while it was handled, allowing it to be compressed which caused it to thin. The duct was then placed in the freezer to make the core stiff. Thinning the core pieces and freezing them to make them hard facilitated their removal. The cast urethane air inlet duct is presented in Figure 48.

Clay parts were made from Chevot Clay® using the machined aluminum molds for forming to the face. The machined molds provided the basic shape, but the elbow in the duct was altered to minimize any interference with headphone earcups which could be worn by the LPM wearer. A large radius turn was present in the machined mold to minimize air flow resistance. However, the sharp turn will minimize interference. A heat gun was used to soften the clay which could then be pushed down to conform to the sculpted lens holder. The air inlet ducts were inserted into the air passages of the sculpted lens holder. The final sculpted air inlet ducts are presented in Figure 49.

A two-piece female mold was constructed of each air inlet duct using meta-filled epoxy (Appendix D, no. 20) for strength and durability. The first several layers were applied as thin coats for reproducing the details. Thicker coats were then applied to speed up the mold-making process. The first mold piece was cast with two metal dowel pins for registration pins. The mating mold piece was then cast on top of the first piece, after three layers of bees wax/toluene parting compound were applied. After curing, the molds were separated and the clay positive cleaned out and a single, large fill/vent hole was milled into one half of each mold assembly, along the parting surface.

Cores of the air inlet duct flow paths were made using the exterior epoxy molds. Neoprene rubber having a 0.06-inch thickness was glued into the molds to form a liner. This liner simulates where the urethane was to be cast. An epoxy core was then poured from TC 2510 and allowed to cure. This cast core positive was then ground to the desired shape. HS II RTV® silicone molds were then cast about the core positive and allowed to cure. The epoxy core was then removed from the silicone by carefully cutting the silicone apart. This silicone mold was then used to cast clay cores made from a mixture of Chevot Clay® and paraffin. Holes having a diameter of about 0.06 inches were melted into the clay cores along the longitudinal axis, with a spacing of about 1.0 inches. The epoxy exterior molds were then sprayed with Epoxy Parfilm parting compound. The

clay cores were installed into the exterior molds and these molds were assembled. Urethane TC 960 was mixed, devacuumed in the mixing pot, and poured into the molds. After curing, the molds were disassembled. The clay cores were removed by heating the cast parts to about 120°F. The flashing was trimmed from the cast urethane air inlet ducts.

3.4.2.3 Face Seal

Two basic approaches were considered for sealing the air management components to the face: lip seals cast as part of the components or soft foam which would be applied to the bottom of the components. Lip seals are generally used in protective masks, but the decision was made to use a foam seal based on the fit and comfort provided by some snow skiing masks analyzed during fit testing of commercial masks. The soft, pliable foam was felt to require less pressure to form the seal and would be more forgiving to provide a better seal for a number of different wearers. However, the foam used in the snow skiing masks was a open-cell foam which is unsuitable in a protective mask. A design of a single face seal was made where all of the air management components would mount to this seal. As shown in Figure 52, each eye and the nosecup area were separately sealed. As the face seal mold was being fabricated, a search for closed-cell foams was made which would be comfortable to the skin, easily folded, bondable to the other components, castable, durable, and not susceptible to compression set. An open-cell foam could be used if it could be coated with a durable elastomer. Casting of the face seal was felt important for fitting purposes; a face seal was not cut from a flat sheet of foam since the seal thickness can vary at the nose bridge and forming the flat sheet to the face could form leak paths in the seal.

The face seal shape was defined during the three-dimensional sculpting of the face components. The seal thickness after compression on the face was assumed to be about 0.12 inches. A compressed face seal thicker than 0.12 inches would likely result in a larger eye relief and higher mask profile. A representation of this seal was sculpted on the headform along with registration marks on the side of the head. A female plaster mold of Hydrostone® (Appendix D, no. 18) was then made using burlap as reinforcement. A matching head was then made from Hydrostone® to provide a headform having a hard face seal. This latter headform provided a base from which the air management components could be sculpted and formed.

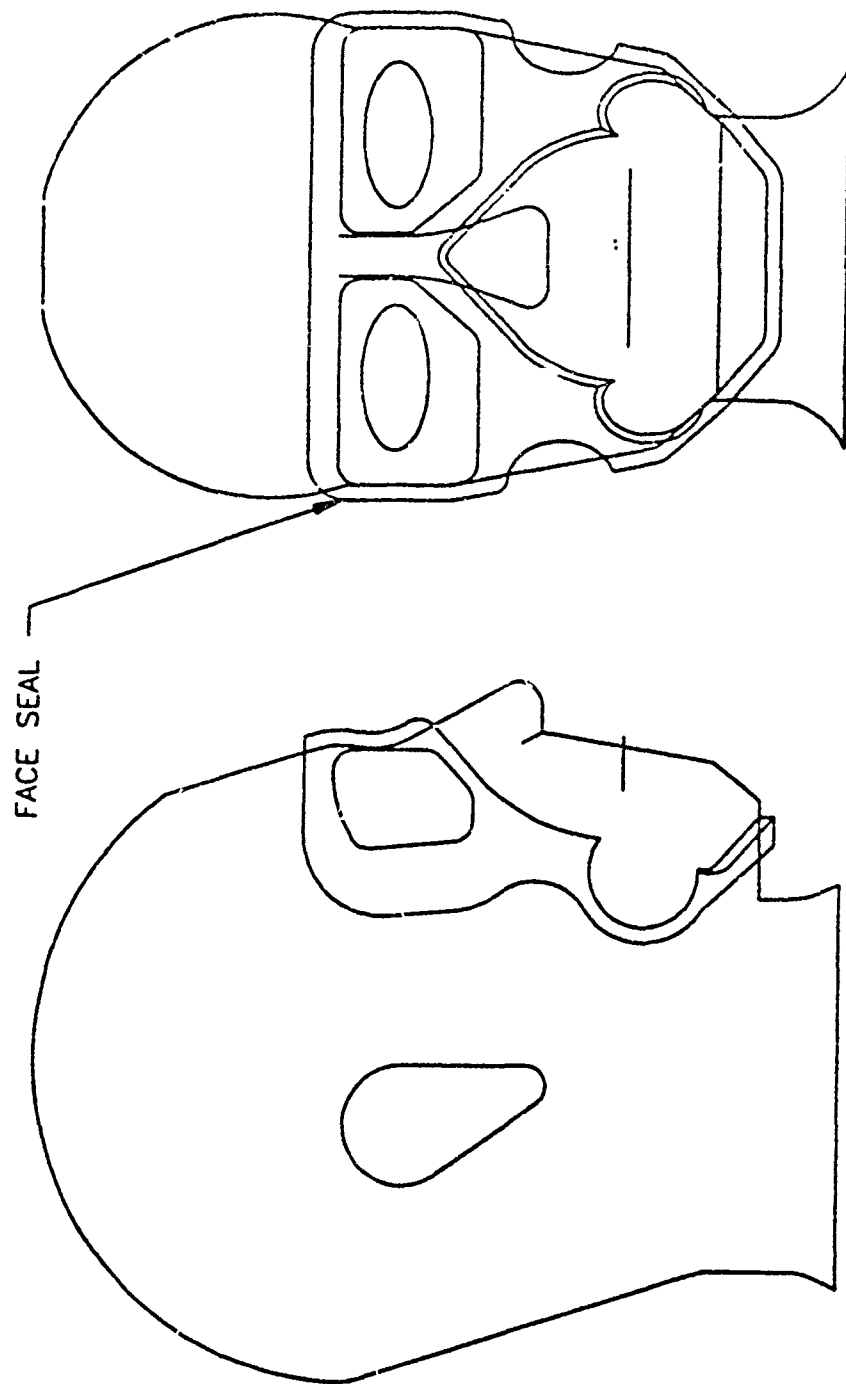


FIGURE 52. FACE SEAL DESIGN

The Hydrostone® face seal molds were used to cast face seals from a flexible pour-in-place polyurethane foam, TC 274 (Appendix D, no. 9). This foam is a 90 second foam which means minimal time is allowed to mix and pour the foam in place. The mixed foam resin was poured into the female mold and the male head placed into position. After a number of face seals were made, the female mold broke due to the hydraulic pressure caused by the foaming action. This broken mold half was not damaged in the face seal area and the reinforcing burlap kept all the broken pieces intact.

Because it was still intact, it was possible to make a new male mold from the broken female mold. Because the original Hydrostone® male head only represented a "compressed" face seal, the new male mold was made with indentations to cast "uncompressed" face seals. The face seal cavity in the female mold was filled with soft clay and leveled to the face surface. This clay was then extracted out. Some more clay was placed into this cavity to fill in the face seal and leveled off. The first clay face seal was then placed on top of the second clay face seal still in the female Hydrostone® mold. An epoxy male mold half was then cast inside of the clay-filled female Hydrostone® mold. The clay face seals formed a face seal indentation in the epoxy male half which would result in the final foam face seals to be compressed approximately 50 percent to result in a compressed face seal thickness of 0.12 inches. The molding epoxy was an aluminum-filled casting epoxy (Appendix D, no. 20) which can withstand relatively high temperatures. Several layers of parting compound consisting of beeswax and toluene were applied with each layer being buffed after curing. This epoxy was applied in layers to provide replication of the details and because an exothermic reaction occurs during curing. After the first number of layers were formed, fiberglass cloth was imbedded with the epoxy layers for reinforcing and to provide bulk to the mold. After the male mold was completed, the female Hydrostone® half was removed. Parting compound was applied to the epoxy male half and the two clay face seals placed on the male headform. A female epoxy mold half was then formed on top of this assembly using the same procedures to make the male epoxy mold half. Some difficulty was encountered while trying to separate the two mold halves, but heating them facilitated disassembly. The clay was removed from the epoxy molds and the molds cleaned. A vent hole, 0.25 inches in diameter, was drilled into the female mold at each inhalation check valve assembly duct to relieve the pressure caused by the foaming resin. The vent holes were needed to prevent any breaking of the molds. The male epoxy mold half was not filled in completely with epoxy due to the time required to complete this, so this cavity was filled in with Ultracal 30® (Appendix D, no. 19) which is similar to Hydrostone® except that the former has higher strength. The Ultracal 30® was applied in layers to minimize shrinkage which could possibly deform the epoxy

mold. The intent of filling the male epoxy mold was to provide both strength and rigidity. The finished epoxy face seal mold halves are shown in Figure 53.

A number of materials were cast in the face seal mold, including urethane foam and silicone foam. The urethane foam, TC 274, was the same used in the Hydrostone® face seal mold. This two-part foam was carefully weighed. The vent holes were taped over on the outside of the female mold. The female mold was then turned over to act as a container. The two foam components were then quickly mixed and poured into the female mold. The placement of the foam resin was insignificant because the male mold was then lowered into the female mold. Because these molds fit together very well, the foam resin is displaced into the proper face seal cavity and it would foam into place. The mold assembly was then turned over and the male head placed on the work bench. The tape covering the vent holes was then removed and the foam would generally start to vent profusely by this time. The female mold was held down on the male mold to keep it from raising up due to the foam pressure. The resulting foam was very soft and flexible, but a strong skinning effect was not obtained. About ten urethane foam seals were made in this manner. One urethane foam seal was made with the same approach, except that the vent holes were covered up in an attempt to increase the foam density. However, the female mold started to rise from the male mold. Clamping the female mold down was not considered in light of the previous Hydrostone® mold breaking under similar circumstances.

Two silicone foams were cast in the epoxy face seal mold. One silicone foam, 3-6548 Silicone RTV foam (Appendix D, no. 29), was a two-part foam which must be poured in 1 minute. The cast foam is black in color. This closed-cell foam was relatively stiff and formed an outer skin, but the strength was unacceptable. The second silicone foam, RTF 762 (Appendix D, no. 30), was a 14 minute foam which provided plenty of time for mixing and applying to the mold. When mixing the two parts, the viscosity was higher than the other foams. After the resin was mixed, it was brushed into the face seal cavity and the mold then assembled. Because the foaming occurred over a longer period of time with less force, the two mold halves were clamped to the table and the vent holes left unobstructed. The resulting white-colored foam had relatively small pores, skinned on the exterior surfaces, and was fairly stiff. In a bench top experiment, the ratio of activator to base was

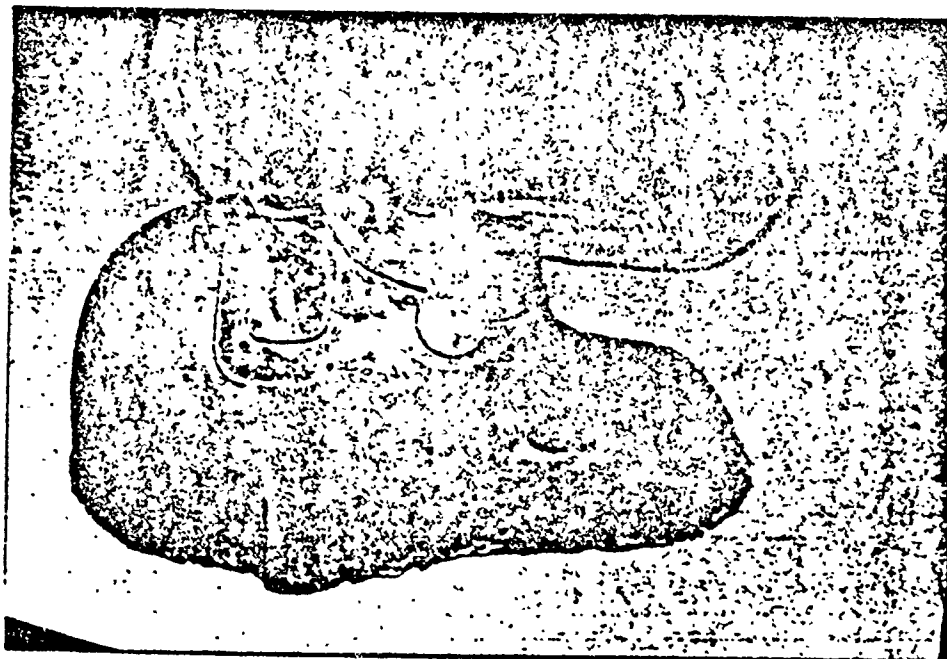


FIGURE 53. EPOXY FACE SEAL MOLD

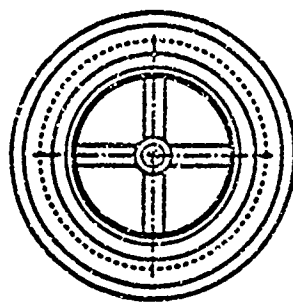
doubled in an effort to reduce the stiffness. However, the stiffness did not greatly change, but the size of pores increased and the skinning effect decreased. Both of the latter results were undesirable.

The urethane foam provided the basic characteristics desired for the face piece, including the tear strength, softness, and comfort to the skin. However, as was verified during casting of the lens holder, the urethane foam is open-cell which is not desirable for the LPM face seal. The silicone foams are closed-cell, except that they did not have the desired physical characteristics of the urethane foam. In general, silicone rubbers are less susceptible to compression set than urethanes, but no information was obtained for the specific foams fabricated and no compression tests were performed. In addition to the physical characteristics, the urethane was found to be readily bonded to the cast urethane while the silicone foam was not readily bonded during some simple adhesive tests. To facilitate the prototyping of the LPM, the urethane foam was used to demonstrate the feasibility of the foam face seal. These seals were not coated with an elastomer which would have increased the stiffness of the seal. As part of a follow on task, the search for a silicone foam or alternative closed-cell foam should be continued which will provide the strength, durability, and softness characteristics without irritating the wearer's skin. One possible candidate is Kraton® foam which is formed in a blow-molding process.

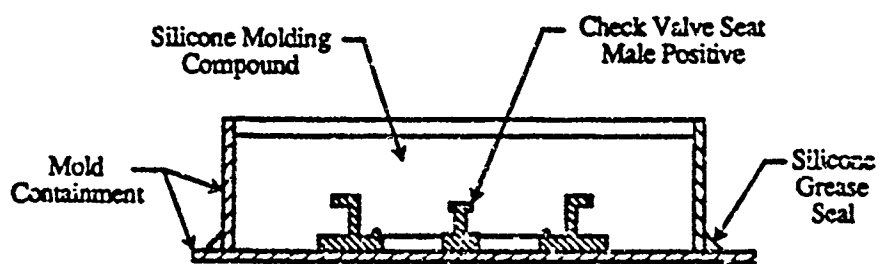
3.4.2.4 Exhaust Check Valve Assembly

As discussed in Section 3.3.2.2 above, the exhaust check valve was based on the convoluted check valve design having the post attachment. CRDEC has previously been making these flappers; therefore, no attempt was made to mold this part. The check valve seat was designed based on the dimensioned drawing provided by CRDEC. The LPM exhaust check valve seat was modified slightly to facilitate molding and to integrate it with the LPM facepiece and exhaust check valve cover (refer to Figure 54). Both the CRDEC and LPM dimensioned drawings are presented in Appendix C.

To fabricate the exhaust check valve seat, a soft, bendable mold approach was used due to the number of undercuts in the male positive. A master male positive was first machined from aluminum. This aluminum positive was attached to an aluminum plate with brittle, fast-acting adhesive (Appendix D, no. 31). A circular cylinder, open on the top and bottom, was placed over the center of the male positive to form the female mold enclosure (refer to Figure 54). This can was then sealed to the base plate with silicone vacuum grease and the entire mold interior sprayed with



Check Valve Seat



Cross-Sectional View of
Check Valve Seat Mold

FIGURE 54. EXHAUST CHECK VALVE SEAT AND MOLD

silicone mold release. A flexible silicone molding compound was then mixed and poured into the container and allowed to cure. This cured assembly was then taken apart to provide an open-face, soft female mold of silicone rubber. Various polymer systems were then used to cast exhaust check valve assemblies.

A transparent silicone molding compound, Sylgard® 182 (Appendix D, no. 13), was first used to make the check valve seat mold. This two-part, low viscosity silicone was mixed together and placed in a vacuum chamber while still in the mixing cup. Once the air bubbles were removed, the silicone was poured into the female mold container. Slowly rotating the female mold about allowed any air bubbles trapped underneath the undercuts of the positive part to rise. The poured mold was then placed in an oven at 150° F for at least four hours. The cured silicone was then removed from the mold container to form an open casting mold. This mold replicated the details of the positive part very well and it could readily be flexed to remove the cast parts. The transparency of Sylgard® 182 also allowed air bubbles in the mold itself and the polymer resin of the check valve seat to be readily identified. Several polymer resins were then cast in the female mold, including:

- Master Mend™ Epoxy TM-51, 5-minute cure time (Appendix D, no. 2)
- Master Mend™ Epoxy QM-60, 90-minute cure time (Appendix D, no. 1)
- Acrylic casting resin (Appendix D, no. 3)
- Polyester resin (Appendix D, no. 4)
- Acrylic urethane (Appendix D, no. 5)
- Acrylated epoxy (Appendix D, no. 6)

Each of the candidate polymer resins were evacuated immediately after mixing. The resins were then carefully poured into the female mold. Because of the mold undercuts at the center post and the outer rim, the poured molds were placed in the vacuum chamber.

Some problems were encountered with the Sylgard® 182 female molds due to a lack of strength of the silicone, but also due to the polymer systems used to cast the first check valve seat parts. All of the resin systems listed above either did not provide sufficient strength (i.e., the check valve seat post stem broke during demolding) or a large number of air bubbles were trapped in the cast parts. None of the above polymers were found suitable for casting the exhaust check valve seats. In addition, the broken post stems could not be easily removed from the Sylgard® 182 female molds. These molds were damaged while trying to extract the broken center posts.

New exhaust check valve seat molds were then cast with a silicone rubber, HS II RTV[®] (Appendix D, no. 16), having higher strength than Sylgard[®] 182. HS II RTV[®] is a two-part, low viscosity, room temperature curing silicone having an opaque white color. The mixed silicone was evacuated in the vacuum chamber while still in the mixing cup, but not after the mold was poured.

Using the HS II RTV[®] silicone molds, check valve seats were cast with an epoxy, TC 2510 (Appendix D, no. 10). This two-part, low viscosity epoxy is transparent, has a pot life of 25 to 30 minutes, and provides good strength properties. The resin was evacuated while in the mixing pot and after pouring into the mold. The cast parts were relatively easy to demold and the center post didn't break off during demolding. The final epoxy inhalation check valve seats are shown in Figure 55.

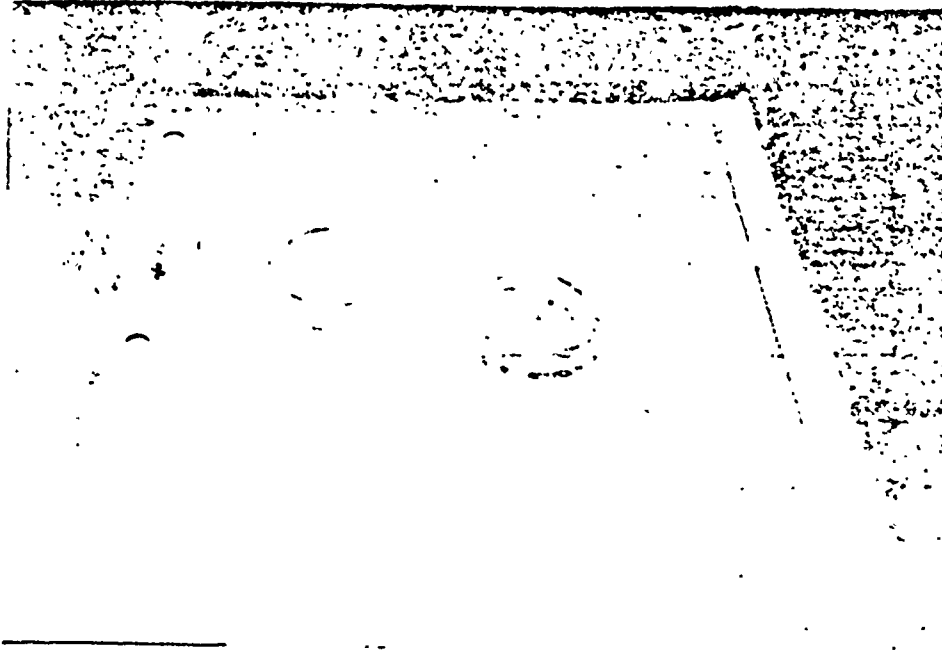


FIGURE 55. EPOXY EXHALATION CHECK VALVE SEATS

Exhaust check valve covers were provided to Battelle by CRDEC. These covers were transparent and included a drinking tube holder. Holes were cut into the front face of the cover for exhaling. This cover fit onto the exhaust check valve seats cast for the LPM prototypes; therefore, they could be used without modification. An unsuccessful attempt was made to cast new covers based on the CRDEC-supplied covers for comparison. A cover was modified by removing the drinking tube holder and by "filling" in the exhalation holes. A urethane casting of this modified cover would then have holes cut into its bottom edge. HS II RTV[®] was used to form a female mold due to the mounting lip forming an undercut. However, the resulting mold would not have been able to form covers having the good appearance of the supplied covers. Therefore, the cover fabrication effort was discontinued and the furnished covers used in the LPM prototypes.

3.4.3 Filter Assembly

The filter assembly development consisted of identifying the filtration media, completing the design, and prototyping the selected design. These design stages are presented in the following sections.

3.4.3.1 Filtration Materials

The design of the filter is based on a study of a flexible filtration system for RESPO 21 completed by Battelle's Aerosol Science and Technology Department.(ref 37) The objective of this study was to identify and evaluate filtration materials for a RESPO 21 flexible filtration system, relative to:

- Air flow resistance
- Aerosol filtration efficiency
- Gas life
- Size
- Flexibility

The final filter models were constructed to provide a DMMP gas life of at least 110 minutes and particulate filtration for 0.3 μ m diameter particles. The cross-sectional area was taken to be 50 in². A filter model based on the current C-18 filter resulted in the thinnest filter, 15 to 17 mm (includes only the filtration media), but it had a pressure drop of 42 to 45 mm H₂O. The aerosol filtration medium of this filter is referred to as C-18 backing while the gas absorption medium is referred to as C-18 charcoal core. This filter model consisted of 8 to 9 C-18 charcoal core layers sandwiched by 2 layers of C-18 backing. A filter model using Filtrete® G0130, produced by 3M, for aerosol filtration and Nanosorb® T301-11, produced by Blücher, for gas absorption provides very low flow resistance of about 8 mm H₂O. This filter consists of 2 layers of Nanosorb® T301-11 sandwiched by 2 layers of Filtrete® G0130. However, the Filtrete® G0130 is an electrostatic particulate filter which would require further evaluation for RESPO 21 respiratory protection. The ability of this material to retain its electrostatic properties during field use including the long-term effect of high humidity is not known. The filter also has a relatively large thickness of about 30 mm (includes only the filtration media).

The filter models were then evaluated based on a cross-sectional area of 100 in². The intent was to minimize the thickness of the filter assembly at the expense of increased area. The thinner filter would have a lower profile and it may provide less interference with the wearer's other equipment. The filter consisting of C-18 charcoal core and backing materials resulted in a filter media thickness of 11 mm and a pressure drop of 15 mm H₂O. This filter model consisted of 5 C-18 charcoal layers sandwiched by 2 layers of C-18 backing material. The Filtrete® G0130 and Nanosorb® T301-11 filter model had a filter media thickness of 19 mm, but the flow resistance was only 4 mm H₂O. One layer of Nanosorb® T301-11 was sandwiched by 2 layers of Filtrete® G0130.

Two filter media designs were studied for the LPM filter assembly: a 100-in² filter composed of C-18 charcoal core and backing, and a 50-in² filter consisting of Filtrete® G0130 and Nanosorb® T301-11. The thinner 100-in² filter would provide a low profile and an acceptable pressure drop. The 50-in² filter would not protrude as low on the wearer's chest and would result in very low flow resistance.

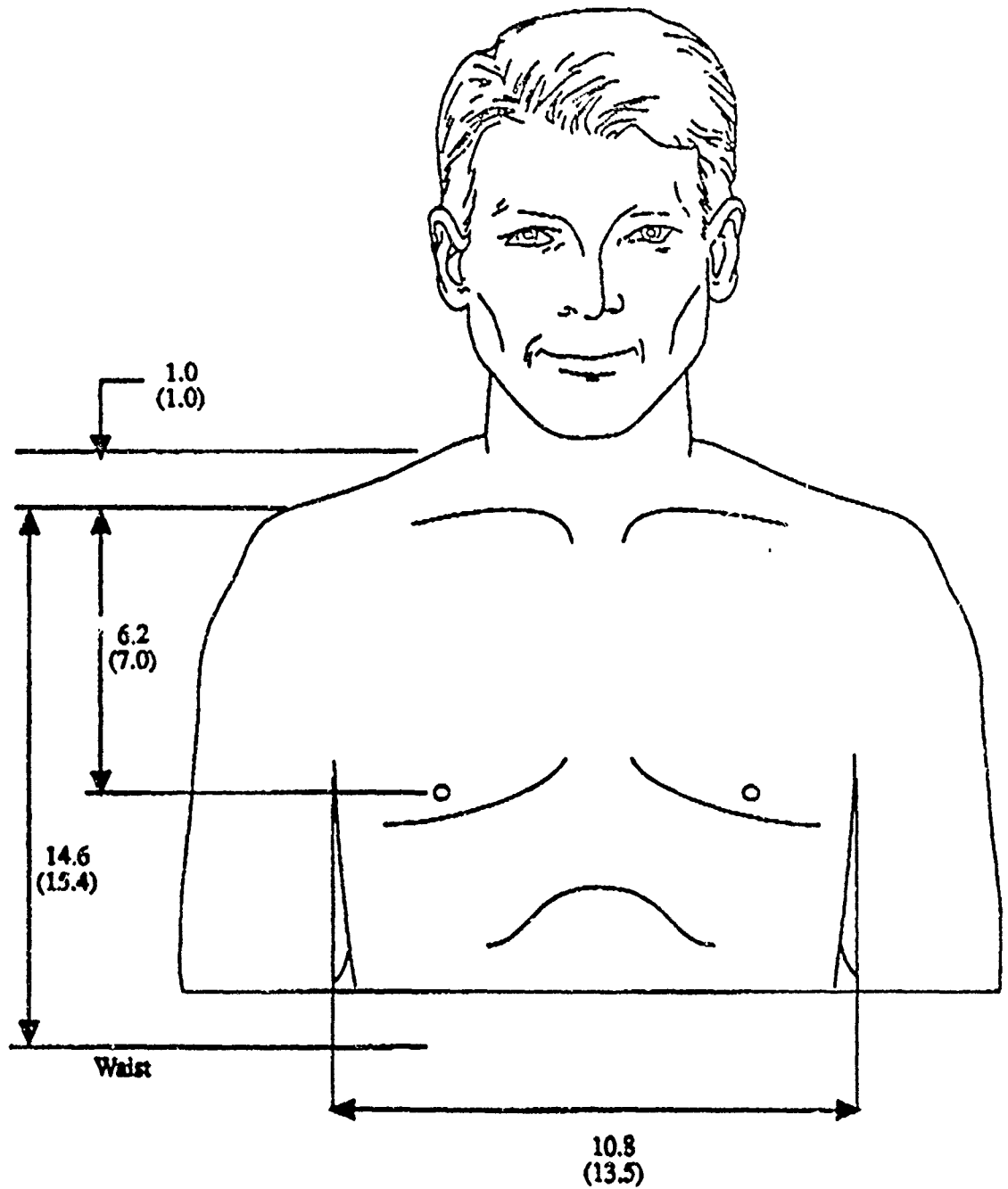
3.4.3.2 Filter Assembly Design

The filter assembly is to be worn on the chest. It is to be flexible for a comfortable fit and for smaller storage volume requirements. Because the filter would not likely provide the 24-hour protection time of the LPM, a safe and quick method of replacing the filter must be provided.

The area available for a chest-mounted filter is shown in Figure 56, relative to the ground troops of MIL-STD-1472C.(ref 31) The width of the filter assembly should not extend over the wearer's arms due to interference with arm movements, such as during walking. Because several sizes of filters were not considered due to the accompanying logistics burden, the width of the filter assembly should be kept under 10.8 inches.

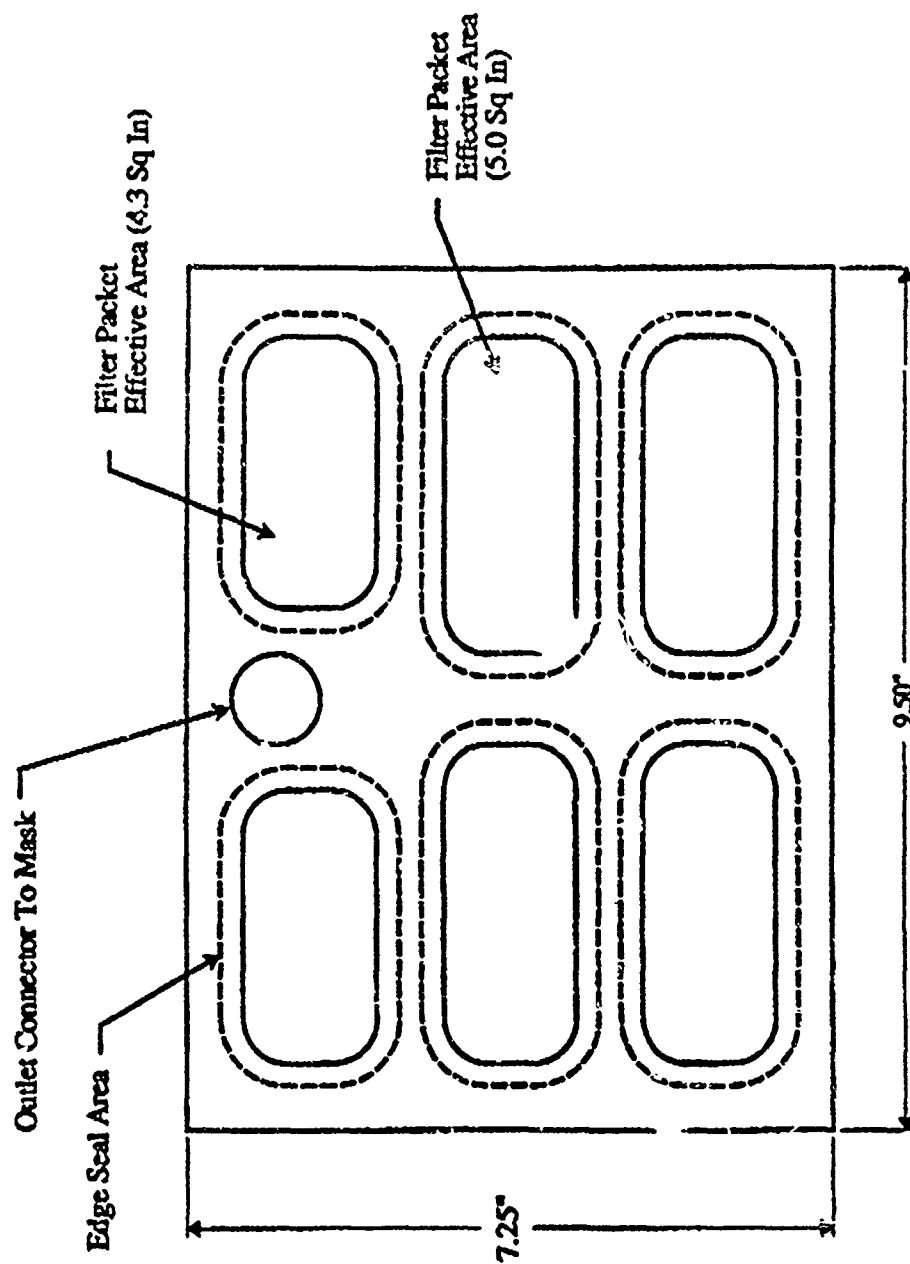
To facilitate folding the filter assembly, the initial design approach was to use approximately six filter packets connected by common air ducting. Air would pass perpendicular to the large filter cross-sectional area of the filter packets, through the filtration media, through the common ducting network to an outlet connector. The filter packets would need to be sealed completely about the edges to prevent air from bypassing the filtration media. Sufficient clearance would be needed between the filter packets for folding. As shown in Figure 57, the total cross-sectional area of an example of this design, not including the edge seal, would be about 30 in². However, the filtration media study (ref 37) found that an area of 45 to 50 in² would be required for an acceptable pressure drop and that a cross-sectional area of 100 in² could provide a low pressure drop in a low profile filter. Because the area on the chest is limited, the filter packets would have to be designed for a high packing efficiency. As the number of filter packets is increased, the size of the individual packets will decrease and the perimeter around all of the packets will increase. The perimeter is important since an edge seal is required around each filter packet to prevent leakage around the filtration media. Therefore, as the number of filter packets increase, the wasted area due to the edge seal is increased. Figure 58 shows a filter layout having two filter packets with an effective filtration cross-sectional area of 40 in², an increase of 30 percent over the layout of Figure 57. One method of increasing the filter size without increasing the filter area required on the chest is to have air enter the filter assembly from the front of the filter and from the back of the filter. The air would then flow through the filtration media into a duct network halfway between the front and back surfaces of the filter assembly. However, the filtration material dimensions resulting from the filtration media study would require a very thick filter assembly which would protrude too far from

AD A 253 085



Dimensions are Based on Ground Troops of MIL-STD-1472C
5 Percentile are Primary Dimensions; 95 Percentile are in Parentheses
All Dimensions are in Inches

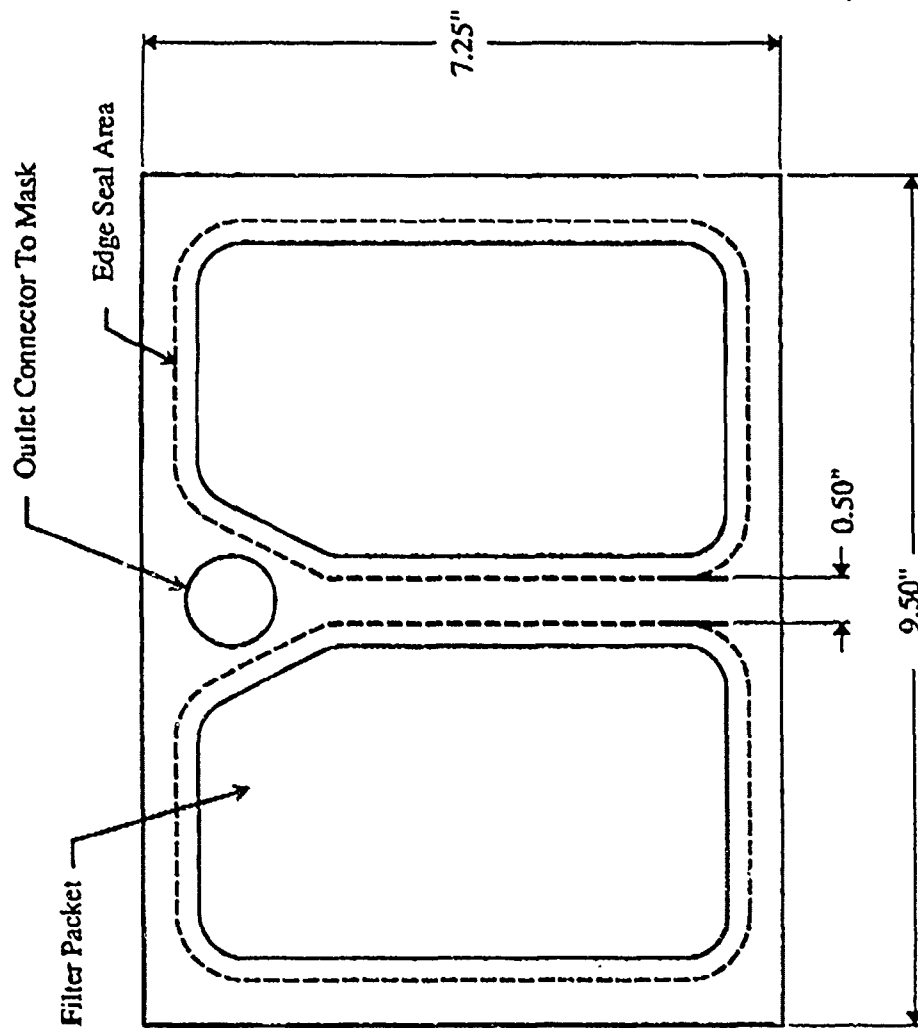
FIGURE 36. AREA AVAILABLE FOR FILTER ASSEMBLY



Drawn In Half Scale

Total Effective Fiber Area is 28.6 Square Inches

FIGURE 57. INITIAL FILTER ASSEMBLY LAYOUT



Drawn In Half Scale

Effective Filter Area Per Packet is 20 Square Inches
Total Effective Filter Area is 40 Square Inches

FIGURE 58. FILTER ASSEMBLY: TWO FILTER PACKETS

the chest. Also, the back of the filter assembly would have to be supported away from the wearer's chest for proper air flow, further increasing the profile.

Therefore, using both the front and back surfaces of the filter assembly for air inlets was not pursued. To provide the most filter possible in the available area for chest mounting, the LPM filter design would be either a one or two filter packet design.

Since the filter capacity will be limited to less than the 24-hour protection to be provided by the mask, the filter elements must be replaceable in the field. To facilitate this replacement, the edge seals around the filter elements should be a part of the replaced filter to best insure that a positive seal is always made. This design approach could be attained by either incorporating the filter assembly into a replaceable hood bib, attached to the rest of the mask by hooks or a zipper or by fitting the replaceable filter assembly into an easily accessible pocket located on the front of the hood bib. A snap-fit connector between the filter assembly and the air inlet ducts would allow easy and quick filter replacement without requiring any tools. The design approach for the LPM filter assembly was to minimize the amount of material which would need to be replaced while providing the best seal possible. This design incorporates the aerosol filtration material, the gas absorption material, and the duct network together into a sealed packet with a single connector to attach to the air inlet duct. Because each filter packet will have its own connector, loosely woven spacer fabric was used to form the duct between the filtration media and the connector. The hood bib would be permanently attached to the hood and a pocket on the front of the hood bib would hold the filter assembly. So that the different components could be designed and fabricated in parallel, two snap-fit connectors would always be incorporated, even for a one filter packet design, so that flexibility in the development process would not be compromised. The two-connector approach provides a low profile when compared to a single connector which would have to have a flow area twice the size since it would need to duct all of the wearer's air intake. However, the two-connector design does make it more difficult to incorporate an optional blower than a single-connector design.

Figure 59 shows two types of woven spacer fabrics considered for use in the LPM. One spacer material is woven from Saran® fibers (Appendix D, no. 22) while the other is an Olefin spacer material (Appendix D, no. 21). The former spacer material is very flexible compared to the latter material. However, the latter material is a more open weave which will provide less air flow resistance.

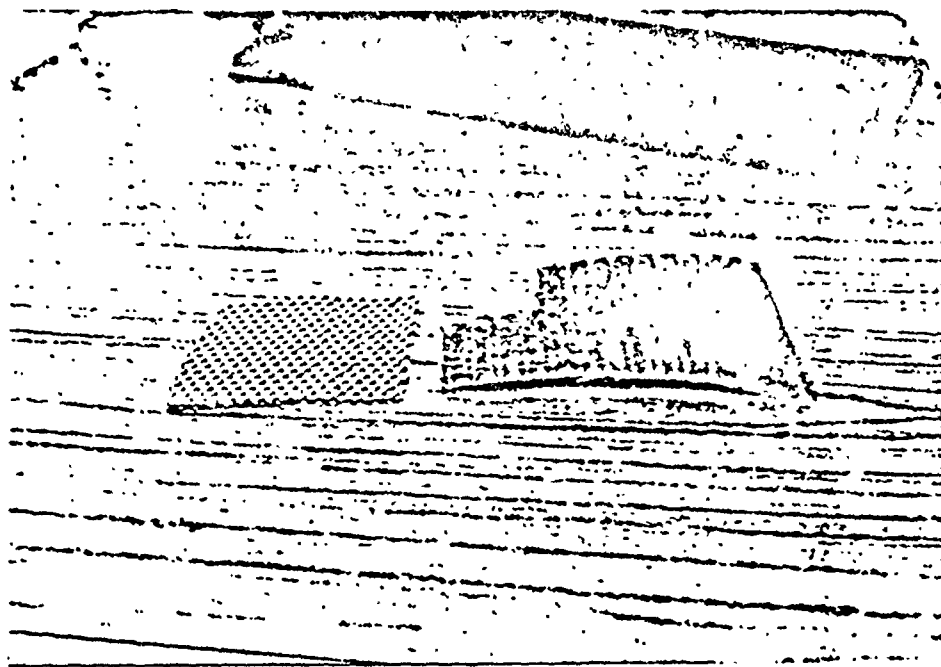


FIGURE 59. WOVEN SPACE MATERIAL

Therefore, the more open Olefin spacer material was used in the LPM filter assembly prototypes. This spacer material is more flexible in one direction than the other and can be oriented in the filter assembly prototype to facilitate folding.

The construction of the filter packets, in order of the air flow path, consists of the following layers:

- The first layer is a mesh fabric to help retain the filtration media layers and is more critical for larger filter packet sizes since the filtration mediums are generally more fragile (i.e., have less strength).
- All of the gas absorption layers (i.e., carbon layers) are sandwiched by two aerosol filtration layers (i.e., particulate filters).
- The filtration layers are succeeded by the woven spacer material for ducting air to the filter connector.
- A thin-film barrier is the last layer to provide the chemical barrier.

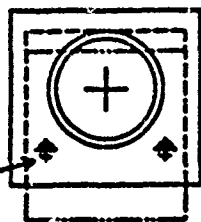
- The edges of the various layers are completely sealed with an elastomer to allow flexibility and sufficient chemical agent permeation resistance exceeding the expected life of the filter capacity.

The thin-film chemical barrier provides a low weight seal for the filtered air. A number of chemical barrier films, such as a Saran®-based laminate or a Teflon® film, can be used to provide about 6 hours of breakthrough chemical agent breakthrough time while being flexible (stretchiness is not required). This chemical barrier could be formed by the same elastomer used to seal the edges, except that the elastomer would likely need to be about 0.06 inches thick and have a higher weight than the thin-film barrier.

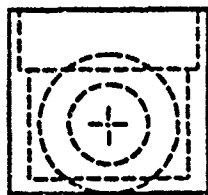
A snap-fit connector was designed (refer to Figure 60) where the male connector half fits over the air inlet duct and the female half fits onto the filter assembly. The male connector was designed to fit over the air inlet duct to preclude causing a reduction in flow area and a corresponding increase in flow resistance. The male connector transitions from the low profile of the rectangular air inlet duct to a round male connector which will accommodate an O-ring for improved sealing. Likewise, the female connector transitions the round O-ring connection to the rectangular profile of the spacer material. The spacer material protrudes from the top edge of the filter assembly, into the male connector. Two hex nuts were molded in place to positively hold the spacer material to the female connector by inserting two screws through the back plate. This back plate was made from aluminum sheet metal to reduce the fabrication time and to simplify the female connector mold. The interference of the snap-fit connection was increased so that a positive lock would occur for the flexible urethane used to cast the connectors. For a stiffer material, the interference would need to be reduced. The flexible urethane also simplified the mold design since undercuts could be present in the mold. Dimensioned drawings of the filter connector molds are located in Appendix C.

The two filter assembly designs prototyped were the 50-in² design and the 100-in² design. The front view of these two designs are presented in Figures 61 and 62, respectively. Side views are not shown since they depend upon the specific aerosol filtration and gas absorption media used. In both designs, the edge seal was assumed to be 0.25 inches around the perimeter of the filter packets.

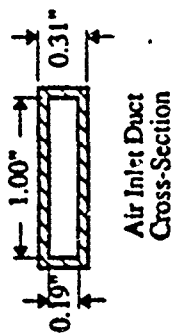
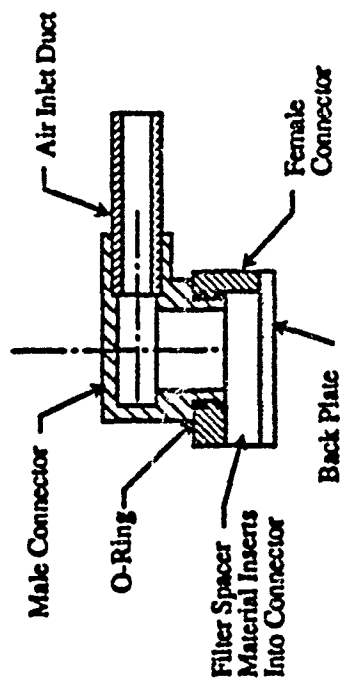
Location of Cast-In-Place Hex Nuts



Female Connector
Top View



Male Connector
Top View



Air Inlet Duct
Cross-Section

FIGURE 60. SNAP-FIT FILTER CONNECTOR ASSEMBLY

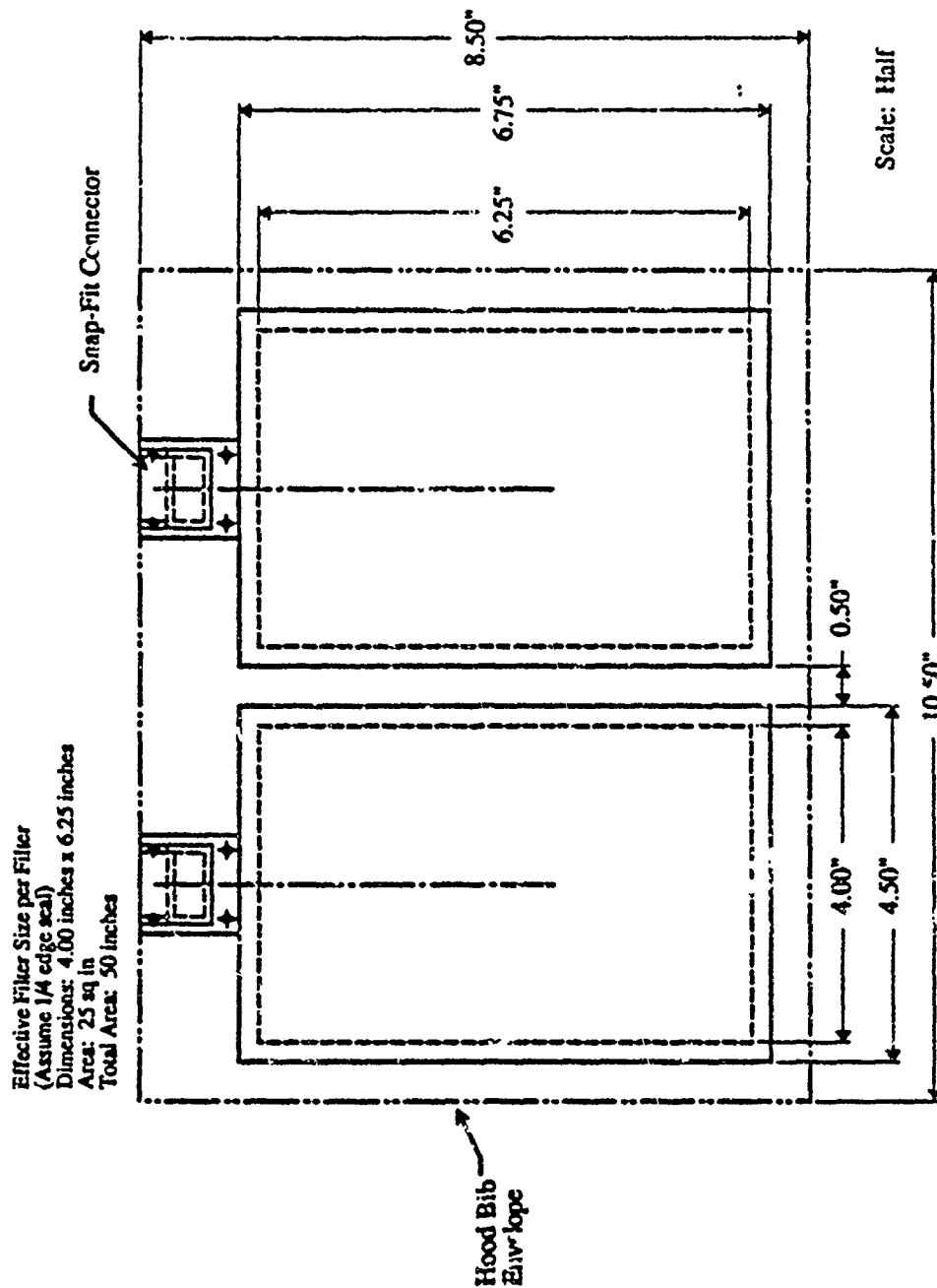


FIGURE 61. FILTER ASSEMBLY: 50 SQ IN

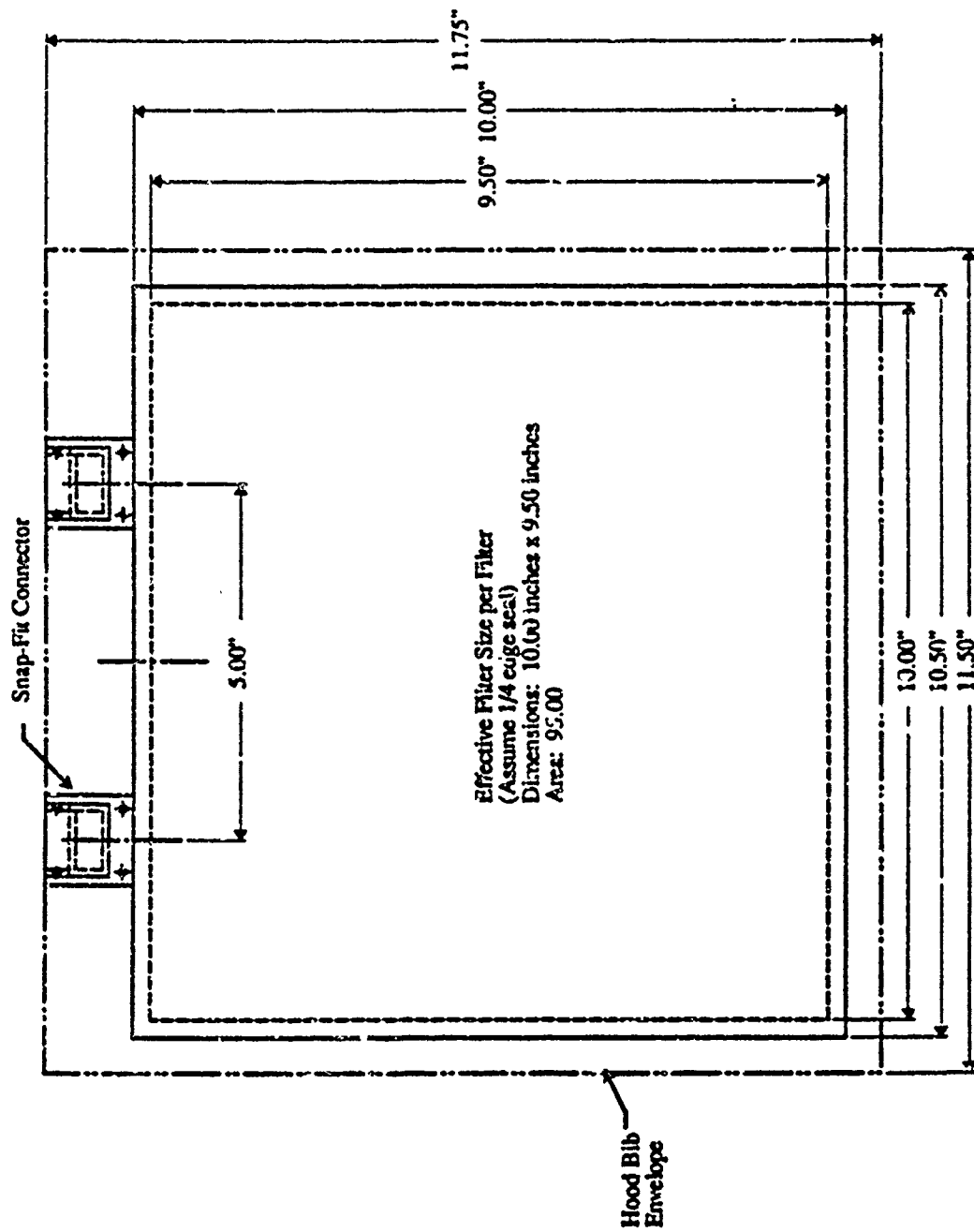


FIGURE 62. FILTER ASSEMBLY: 100 SQ IN

3.4.3.3 Filter Assembly Fabrication

Filter connector molds were first machined from aluminum. Dowel pins were used to register the mold parts together. Silicone parting spray was applied to the mold parts before assembly. Two #2-56 brass screws were inserted through the female mold and brass hex nuts threaded onto the end. A gap of about 0.06 inches was left between the nuts and the aluminum mold and the screw heads were taped in contact with the mold. This action resulted in the urethane totally encapsulating the hex nuts, except for the hole for the screw, thus preventing the nuts from falling out of the cast urethane and allowing the attachment screws to be threaded into the hex nuts during assembly. The female mold Connectors were cast from a urethane, TC 960 (Appendix D, no. 7). This urethane was mixed and degassed while in the mixing pot which required about 5 minutes. Because the urethane was injected into the molds with a syringe, the injection had to be completed before the viscosity began to increase (the pot life is about 25 minutes). The molds were then angled to allow any bubbles in the molds to rise up into the fill and vent holes. The molds were then placed in an oven at about 120°F to shorten the demolding time to about 3 hours. When disassembling the female mold, the screws holding the hex nuts in place were removed first. The urethane, in general, was easy to remove from the aluminum molds. All of the cores were also made from aluminum, so core removal was not difficult. The cast urethane connectors are shown in Figure 63. The aluminum back plates were cut from sheet metal.

Fabricating both the 50-in² and the 100-in² filter assemblies was completed using the same basic approach. The filter elements, including the outer mesh fabric, the aerosol filter material, the gas absorption material, and the thin-film barrier, were cut from the rolls of materials using flat aluminum sheet metal patterns to ensure uniform sizes of material. Saran®, having a 6-mil thickness, was used as the thin-film barrier. The Olefin spacer material was cut to the same size except for the "ears" which are inserted into the female filter connector. Two aluminum sheet metal patterns were then cut so that the stacked filter elements would extend out 0.25 inches all the way around. The stack was assembled and sandwiched by these two aluminum patterns. C-clamps were used to gently hold the stack together, using care to not compress the filter elements. Urethane, TC 960, was then brushed over the exposed 0.25 inches around the stack perimeter to form the U-shaped edge seal. When brushing, the stack was supported off of the workbench and parallel to the bench top, thus preventing the urethane from dripping inside of the spacer material. A number of layers were applied



FIGURE 63. CAST URETHANE FILTER CONNECTORS

to result in a urethane thickness of about 0.60 inches. However, the TC 960 viscosity was too low and was difficult to apply. Fumed silica was added to the urethane as a thixotropic agent with little success. A brush-grade of the TC 960 urethane, called TC 960-B (Appendix D, no. 8), was obtained and used as the edge seal material. This brush-grade urethane could not be devacuumed since this caused premature curing; therefore some bubbles were always present in the cured urethane due to mixing and brushing. After final curing of the urethane, the excess urethane covering the outer aluminum patterns was cut away and the aluminum patterns popped off of the filter assembly.

The 100-in² filter assembly was the design selected for final prototyping due to its small thickness, approximately 0.5 inches. This design consisted of 5 layers of C-18 charcoal core sandwiched by two layers of C-18 backing material. The other filter elements were as discussed above. One 50-in² filter packet (two filter packets required for a complete filter assembly) was fabricated for evaluation purposes. This latter prototype is shown in Figure 64. One layer of Nanosorb® (a type similar to two layers of Nanosorb® T301-11) was sandwiched by two layers of Filtrete® G0130.

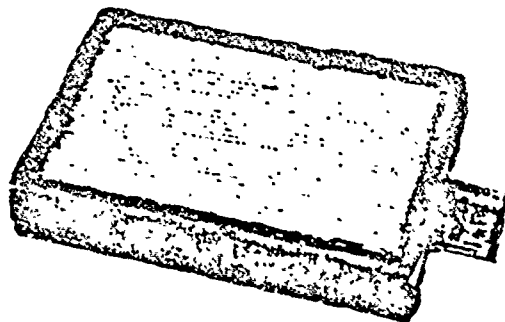


FIGURE 64. 50-IN² FILTER ASSEMBLY PROTOTYPE: ONE FILTER PACKET

3.4.4 Facepiece

The facepiece attaches all of the air management components to the hood. The suspension also attaches to the hood; therefore, the facepiece is common to all of the other components and must be successfully joined in a manner which does not degrade the chemical properties of the facepiece material. The two basic types of facepiece designs investigated are a thermoformed facepiece and a fabric based facepiece made from a non-stretchy material. The original conformal facepiece/hood design was not developed because a stretchy conformal material which provides a high permeation resistance could not be identified. A dip-coated facepiece is integral with the hood; therefore that concept is discussed in the following section

A thermoformed facepiece separate from the hood was explored because it provides a method of conforming to the curvature of the face without introducing seams. The chin is one area where a thermoformed facepiece can be beneficial due to the sharp transitions. Another benefit of a thermoformed facepiece is that the material used can be transparent for personnel recognition, although this is not an LPM requirement.

To thermoform a material, the polymer film is heated close to its melting temperature. The polymer is then forced into the thermoforming by applying a vacuum, pressure, or a combination of both.(ref 38) Vacuum is applied underneath the film while pressure is applied above the film. The low thermal mass of the polymer film generally requires that the film be forced quickly into the mold where it is then allowed to cool into shape. Vacuum is limited to about 12 to 14 psi where 6 to 10 psi is the most common. Pressure forming is not limited and pressures of 50 to 120 psi are normal. If the mold has sharp corners or surface texture, pressure forming is preferred. The thermoformed film will undergo some permanent stretching (i.e, thinning) during this process. This thinning effect is greatest where the gradient of the mold is the greatest. Therefore, in a chemical protection facepiece, the transitions across the face should be smooth to preclude excessive thinning of the barrier.

Two common barrier materials were considered for thermoforming a facepiece: Saran® and Teflon® FEP. Both of these materials are flexible in thin films, but neither one is stretchy. No other materials were identified which can be obtained in a flexible thin-film, thermoformable, and possibly provide 24-hours of chemical agent permeation resistance. A custom laminate may provide these characteristics, but a commercially available laminate which could be implemented into LPM prototyping was not found.

Saran® having a 6-mil thickness and Saranex® having a 4-mil thickness were obtained for testing and evaluation. The Saranex® was not considered strong enough for a facepiece and was not tested. The 6-mil thick Saran® was the thickest which could be obtained and was felt marginally strong enough for facepiece prototyping. However, as discussed in Section 3.2.1.2, this Saran® was fabricated by blow molding which orients the film. When heating the film in preparation for thermoforming, the film disintegrates instead of flowing. Cast Saran® is suitable for thermoforming, but this type could not be found in thicknesses of 5 mils or greater.

Various thickness of Teflon® FEP are readily available; however this material is fairly expensive. FEP is heat sealable and thermoformable, but these processes must be performed at relatively high temperatures of about 550° to 600°F. In addition, adhesives do not readily bond to FEP unless the material is treated for it. Some methods of treatment include electrical discharge process (ref 39), corona discharge, and chemical etching.(ref 40)

Battelle purchased Teflon® FEP having a thickness of 10 mils. This thickness was considered strong enough for the LPM, provided sufficient chemical agent permeation resistance, and was considered thin enough for flexibility. Some trial thermoforming was performed using a face

seal thermoforming mold for the RESPO 21 multilayer mask.(ref 41) In addition, a number of other polymer films were also thermoformed for comparison although these other materials were offer good chemical barriers. Some FEP samples were then sent to a chemical etching company to allow adhesive testing to be performed.(ref 40) This treatment was a sodium ammonite dip process which turns the clear FEP to a "mottled" brown color. The company performing the treatment does not offer a masking capability. This treated FEP was used in testing adhesives for bonding FEP to the urethane used to mold the air management components and to various hood materials. This testing along with the adhesives used can be found in Appendix D. A hood and facepiece prototype was constructed utilizing one of the test thermoform FEP facepieces and coated nylon as the hood. The facepiece was sewn to the coated nylon. This prototype is presented in Figure 65 although the facepiece is hardly visible due to its transparency.

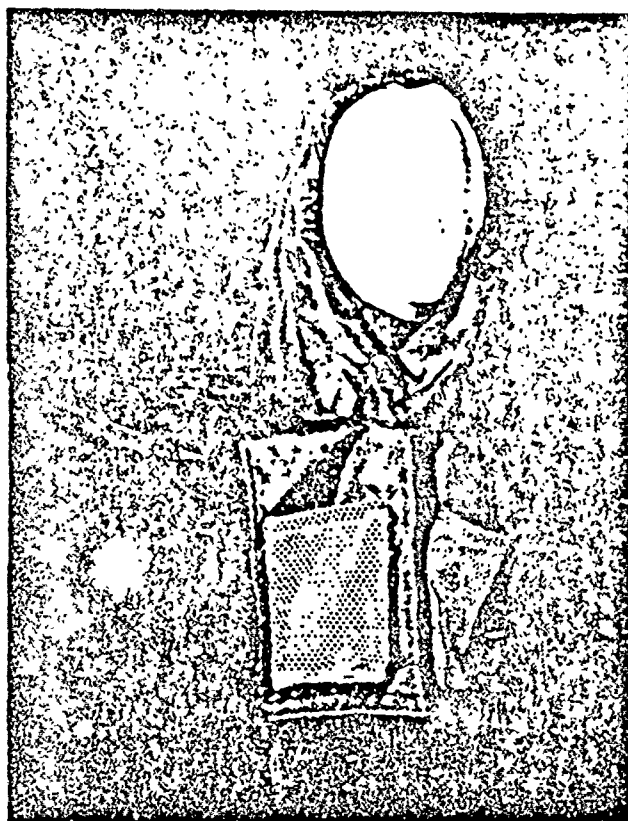


FIGURE 65. THERMOFORMED FACEPIECE AND FABRIC HOOD PROTOTYPE

Although FEP facepieces using the above approaches do provide some benefits, they were not implemented into the final LPM prototypes. The time required to thermoform followed by the time required to chemically etch the FEP (the chemical etching is degraded by heat), did not conform to the delivery schedule of this program.

Since a thermoformed facepiece could not be made from a suitable material and which fit into the development program, a fabric facepiece was used in the final LPM prototypes. The facepiece was constructed from the same impermeable material used to form the hood. As discussed in the following section, semi-permeable materials were considered for the hood. However, these materials were not considered for the facepiece because carbon particles frequently become dislodged from the carbon layer and could be inhaled by the wearer. To provide a close fit, two pleats were placed at the forehead and one pleat used at the chin. A fabric facepiece and hood prototype is presented in Figure 66.



FIGURE 66. FABRIC FACEPIECE AND HOOD PROTOTYPE

The facepiece suspension attaches to the facepiece to provide a sealing force on the face seal. The material used for the suspension is a open fabric of nylon and Lycra® (Appendix D, no. 35) previously identified by CRDEC. The addition of Lycra® is desirable because these fibers provide a high degree of stretch without taking a permanent set. In addition, this fabric withstands hot water during laundering without loss of stretch or strength. Because the suspension material can absorb perspiration and dirt, it is attached to the facepiece by a zipper for easy removal and cleaning. Hook and loop fasteners were provided in the back of the suspension for personal adjustment.

3.4.5 Hood

Three basic hood materials for the LPM were explored: impermeable coated fabrics, semi-permeable coated fabrics, and a dip-coated latex on a fabric substrate. A non-fabric film was not considered for the hood since it was felt that a film thickness suitable for durability would not be flexible enough for a hood.

The dip-coating concept was investigated for hood prototyping by compounding butyl latex and natural rubber latex. Samples were formed onto glass test tubes and test tubes covered with a nylon/Lycra® fabric substrate. However, the formed samples did not have sufficient strength and a smooth coating was difficult to achieve. The dip-coating process is described in further detail in Appendix F. Because additional testing and development would have been required to fabricate a dip-coated mask, this effort was discontinued.

The semi-permeable composite materials discussed in Section 3.2.2 all consisted of a liquid barrier layer and a layer consisting of a material loaded with activated carbon. These two layers combined tend to be bulkier and heavier than the impermeable chemical barriers identified. These disadvantages of the semi-permeable hood are offset by its ability to transmit water vapor, thus reducing the physiological burden on the wearer. However, one question of an impermeable hood versus a semi-permeable hood is whether a lighter in weight impermeable hood providing a complete barrier is more or less of a thermal burden on the wearer than a heavier semi-permeable hood which transmits some water vapor. In addition, the semi-permeable hood materials would need to be joined by sewing where the seams could be covered by an adhesive sealing tape. The impermeable materials, although presently needing sewing and the seams sealed, will likely be capable of being heat sealed (e.g., the Chemfab fluoropolymer coated materials).

Because the impermeable chemical barrier materials identified during the materials search provide lower weights than the semi-permeable materials and show promise of being heat sealed in the near future, the LPM prototypes hoods were fabricated from impermeable coated fabrics. The actual materials selected for LPM hood fabrication were Chemfab's Challenge 4000 (Nomex® coated with fluoropolymer on one side), Chemfab's polyester coated with fluoropolymer on one side, and a coated nylon referred to "pack cloth". The Chemfab materials were selected even though the initial chemical agent testing measure relatively short breakthrough times for HD, because they are similar to the Chemfab nylon coated with fluoropolymer which Chemfab claims provided a breakthrough time of 20 hours for HD. Further development of these materials, along with the ability to heat seal them together, may result in flexible and lightweight LPM hoods and facepieces in the near future. The pack cloth hoods were selected, although this material is not chemical barrier, because it was readily available and there was a lack of good material candidates; this "simulated" chemical barrier does provide the basic strength and durability properties desirable in a hood for field use.

The hood design includes the primary hood, the fabric facepiece, and the hood bib for mounting the filter assembly. Some clearance was provided in the neck area to facilitate donning and doffing. A method of adjustment to seal off the neck area after donning was not provided, but will need to be added at a later development stage. The hood bib includes a pocket made from an open weave material to hold the filter assembly. Although not incorporated into the hood prototypes, straps should be attached to the back of the hood which would run under the wearer's arms and attach to the bottom of the bib. These straps would keep the filter assembly from bouncing around, such as when the wearer is running. The air inlet ducts protrude from inside the hood to the filter assembly. Flaps were attached to the hood to cover the tops of the air inlet ducts exposed outside of the hood; however, the air inlet ducts should be sealed to the hood where this protrusion is made. The hood prototypes were sewn together and a method of sealing these seams will need to be added in the next development. Two hood prototypes constructed from pack cloth are presented in Figures 65 and 66.

3.5 Demonstrator Fabrication

With all of the parts fabricated (as presented in their respective sections above), the various components were assembled into functional prototypes. This assembly was basically performed by adhesives to join and to seal the components together. The air management

components were joined together first using the epoxy face seal mold to hold the face seal. Additional fixtures would have been beneficial because the TC 960 urethane used to fabricate the air management components was used as the joining adhesive. This urethane takes several hours before any strength is developed. Without good holding fixtures, fast-acting adhesive was used to hold the components in place. The urethane was then applied to basically seal the parts together and to provide a flexible adhesive joint. Also, the urethane foam face seal would absorb the low viscosity TC 960 urethane which causes this foam to stiffen; therefore, the brush-grade urethane, TC 960-10 was used to attach the components to the face seal.

With all of the air management components joined together, TC 960-10 was applied to the top surfaces of these components. A sewn facepiece, with some of the hood panels sewn on, was placed on top of the air management components and slight pressure applied until the urethane cured. The rest of the hood was then sewn to the assembled facepiece. The eye holes were then cut from the facepiece and the lens attached to the lens holder using TC 960. The exhaust check valve seat was bonded to the facepiece and the suspension zipped onto the facepiece. Drawings of the LPM prototypes are presented in Figures 67 and 68. Figure 67 was an earlier design prior to developing the snap-fit connectors for the filter assembly. Figure 68 is the finished final prototype design.

3.6 Design Change Recommendations

A number of functional improvements can be made to the LPM prototypes constructed during the performance of this program. Some of the changes are needed because existing components, such as the B/LPS lenses, were implemented into the design to facilitate prototyping even though they did not provide the best design for the LPM. Other changes are needed because the prototyping methods used could not provide the design features as drawn in a timely fashion.

The lenses used in the LPM prototypes were borrowed from an existing lens system to facilitate the prototyping process. Because vision is critical to the performance of a mask, a new lens system design should be developed to provide maximize vision acuity and field of view while maintaining a low profile and minimum eye relief. Because vision is so critical, the air management components should then be modified to accommodate this optimum lens design.

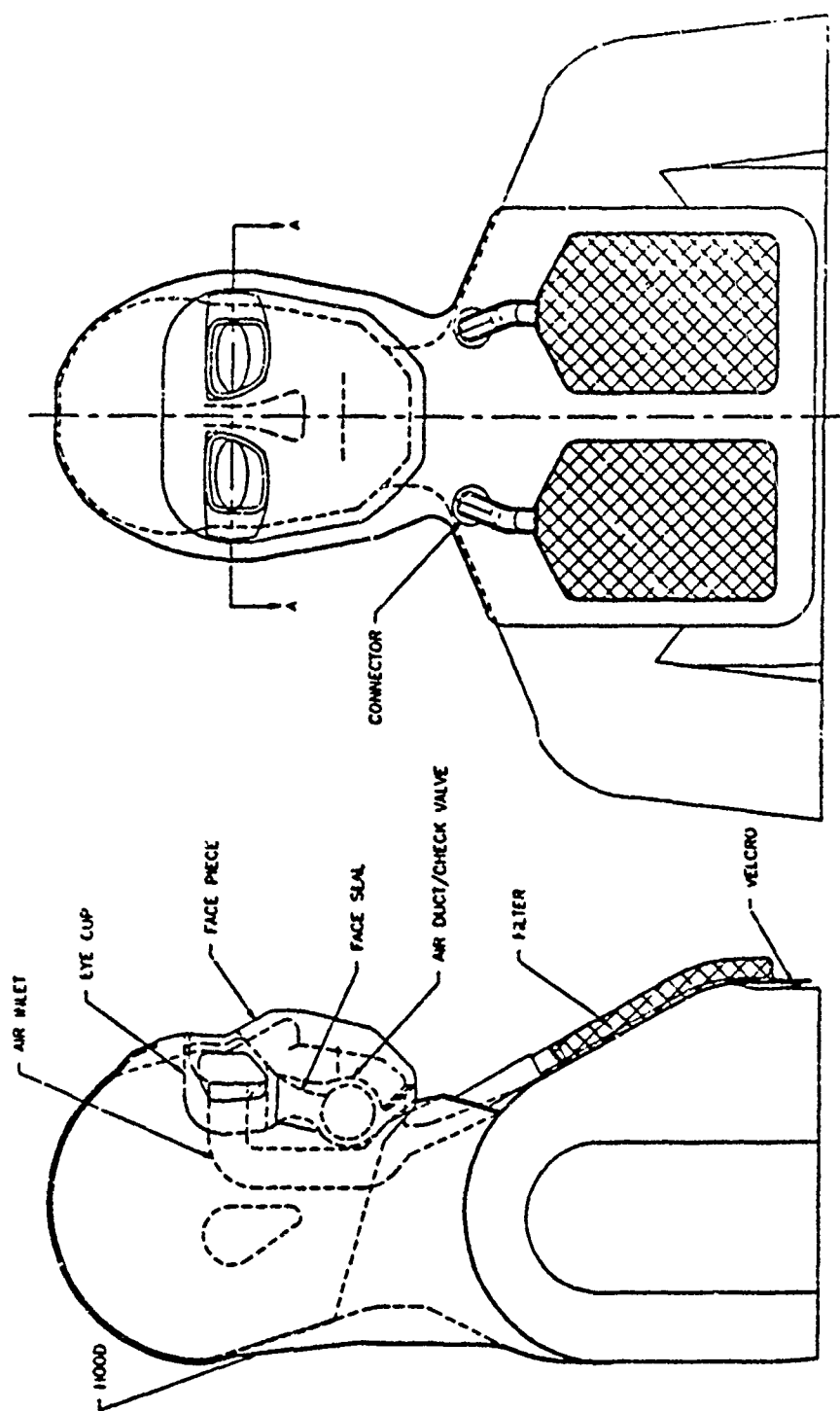


FIGURE 67. PRELIMINARY LPM DESIGN

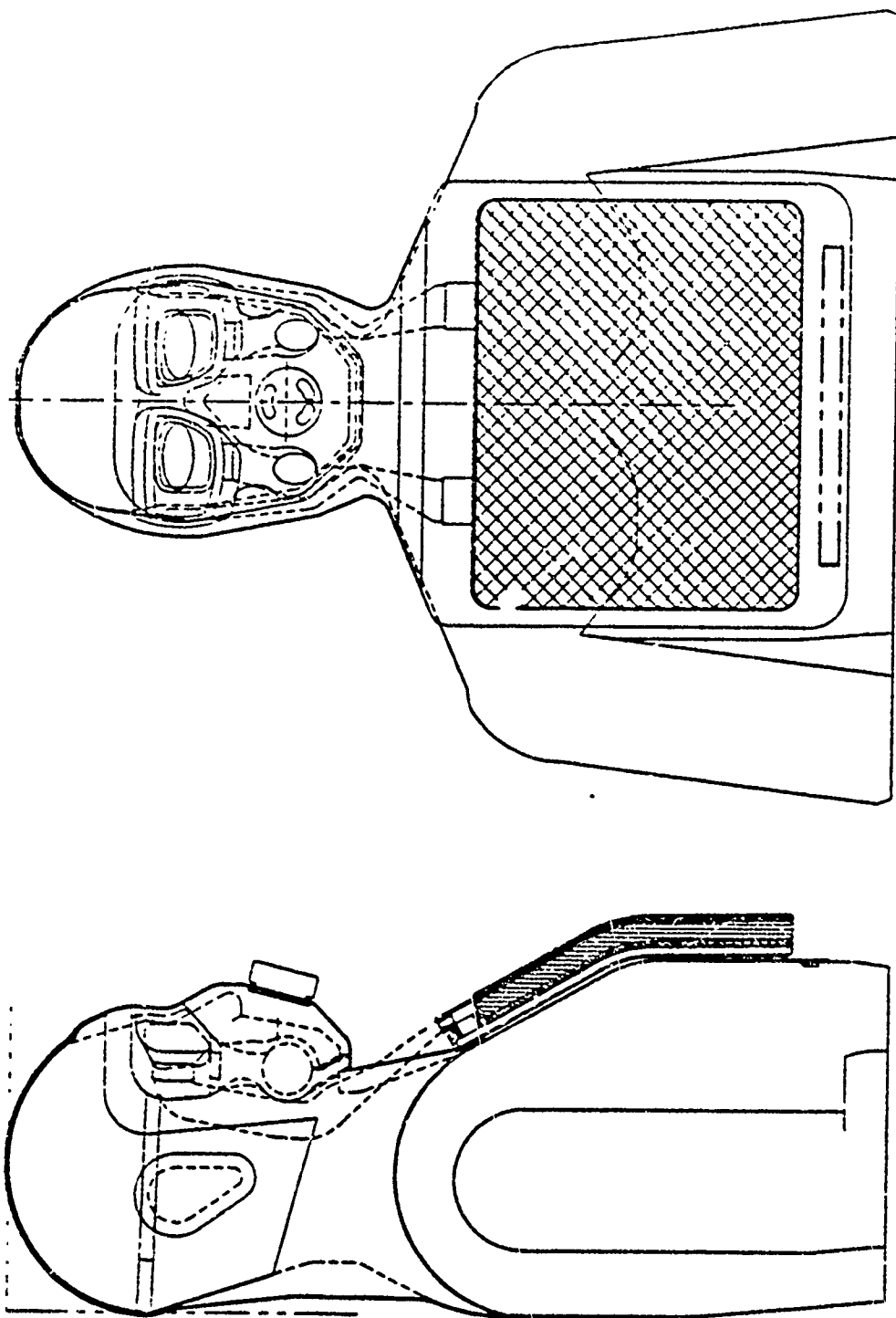


FIGURE 68. LPM PROTOTYPE LAYOUT

As the clay air management components were being formed to the headform, some of their design features were lost. For example, the lens holder should be redesigned to accommodate the laser protection outserts which would attach directly to the lens holder. The LPM prototype facepieces were bonded to the lens holders where the laser protection outserts should be mounted. This occurred because the mounting flange on the lens holder could not be sculpted as designed. A redesigned lens holder should include this separate flange. The mounting channels in the lens holder for the primary lenses are not symmetric about the nose. Care should be taken during future mold generations to be more symmetric. The mounting holes in the lens holder for the optical correction inserts do not fit the molded optical correction insert frames. This occurred because fabricating the optical correction frame molds would have slowed down the lens holder sculpting and molding which was not desirable. The mounting holes in the lens holder for the optical correction inserts need to be modified for a better fit. Also, the dimensions of the air duct air flow paths were slightly reduced during the face-forming process. The air flow resistance should first be measured for the air inlet ducts and the inhalation check valve assemblies to obtain a baseline. If needed, these parts should then be refabricated to increase the flow path area. Because these ducts are rectangular in shape for a low profile, a slight increase in the height will provide a significant increase in the flow path area.

The face seal was fabricated from an open-cell urethane foam because this foam provided the low stiffness desired and was readily bonded to the other air management components. A number of closed-cell silicone foams were used to cast face seals, but they did not provide these characteristics. The search for a suitable closed-cell foam should be continued which could then be cast into face seals.

The prototype hoods do not form a good neck seal. A large neck opening was provided to facilitate donning and doffing of the mask, but a method of sealing around the neck when the mask was on was not provided. A method of making a good neck seal should be added. Retaining straps should also be added which attach the back of the hood to the bottom of the hood bib by passing underneath the wearer's arms. These straps will hold the filter assembly in place on the chest. A method of sealing the air inlet ducts to the hood should also be added where these ducts protrude from the hood to connect to the filter assembly.

Due to time constraints, the chin seal was made from its machined aluminum mold and spliced into the prototype. The chin seal provides the interface between the facepiece and the face seal. Like the inhalation check valve assemblies and the air inlet ducts, a clay chin seal can be

formed to the new form. An epoxy mold can then be made from this clay positive and urethane chin seals fabricated.

4.0 CONCLUSIONS

The LPM design requirements were translated into a design via initial testing and mockup fabrication. This design was then developed into functional prototypes by sculpting and molding the air management components, and by sewing facepieces and hoods. Although all of the materials used to construct the prototypes are not the materials which would be used in production of the LPM, they do simulate the physical characteristics of materials which could be used.

The LPM prototypes which were delivered to CRDEC do show that the LPM concept is feasible. The prototypes are light weight. The vision characteristics of the LPM are very similar or better than many existing protective masks, including the eye relief, field of view, and vision acuity. Improvement in the LPM visual characteristic should also be realized as the design evolves and better (also more expensive) casting processes are used. The casting of the air management components could be improved since the existing casting methods result in excessive flashing which must be trimmed. Improving the casting methods will also improve the quality of the cast parts, such as increased wall thickness uniformity. The LPM prototypes are not as foldable for storage as initially envisioned; however, this is partly due to maximizing the filter assembly size for reduced pressure drop at the expense of foldability. The prototype hood and facepiece materials do not provide 24-hour chemical agent permeation protection, but they are representative of developmental materials which can meet this requirement. These developmental materials are also likely to be capable of heat sealing for hood fabrication, or minimally, tape sealing of the seal seams.

5.0 RECOMMENDATIONS

Because the LPM prototypes do show this concept to be feasible, its development should be pursued. These prototypes provide a low weight and low profile when compared to existing military chemical protection equipment.

A number of materials are presently under development which might be utilized in the LPM facepiece and hood. For instance, Chemfab is developing fluoropolymer-coated fabrics which are lightweight, flexible, and which should be heat sealable. The progress of this development should

be followed, and possibly funded, along with other developer programs to produce both impermeable and semi-permeable materials for chemical protection. Although the development of a stretchy chemical barrier material which conforms exactly to the wearer's face (similar to the stretch properties of nylon/Lycra® fabrics) is not likely in the near term, an effort should be made to encourage this development in the future.

A laminate consisting of an outer chemical barrier and an inner structural layer should be pursued. Because films or coatings which provide excellent chemical agent permeation resistance are typically non-stretchy and stiff, the outer chemical barrier thickness should be minimized. The structural layer should be sufficiently thick for strength and durability while providing flexibility and comfort to the wearer. This laminate should be thermoformable to conform to the wearer while reducing the number of seams. This laminate could also be transparent for personnel recognition. A candidate laminate of this type was not identified during the performance of this program. Because many barrier films and laminates are developed for the food and medical packaging industry, it may be necessary to fund a custom laminate development program specifically for the LPM and similar chemical protection equipment.

As the above materials become available for integrating into the LPM, the molding methods used to fabricate air management components and lenses should be improved to provide better quality parts. Rapid prototyping methods, such as stereolithography, should increase the pace of development (also allowing faster evaluation of the fabricated parts) while allowing more control over material thicknesses and component interfaces. Future developments may also integrate all of the air management components into one mold which would provide higher sealing reliability over the adhesive joining methods.

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APPENDIX A: LIGHTWEIGHT PROTECTIVE MASK DESIGN REQUIREMENTS

APPENDIX A: LIGHTWEIGHT PROTECTIVE MASK DESIGN REQUIREMENTS

Various requirements for the lightweight protective mask (LPM) are provided below. The source for these requirements are from the Developer's Specification (RESPO 21) (Draft copy) provided by Corey Grove, CRDEC. The following specifications are not intended to be all inclusive; they are for reference only.

Requirement	Criteria
System	
Donning time	9 Seconds
Temperature	
Operational	$-25^{\circ}\text{F} \leq T \leq 120^{\circ}\text{F}$
Storage	$-60^{\circ}\text{F} \leq T \leq 160^{\circ}\text{F}$
Life	
Unit/individual	1 Year
Packaged	10 Years
Decontamination	5 decons/30 days (AR 70-71)
Barrier protection	24 hrs @ 10 g/m^3
User group	1% to 99% population
Vision	
Lens standoff	
Optimum	18 mm
Maximum	25 mm
Optics	
Luminous transmittance	$\geq 85\%$
Haze	$\leq 5\%$
Prismatic deviation	
Vertical	≤ 0.18 diopters
Horizontal Sum.	$\leq 0.5^{\wedge}$ diopters
Horizontal Diff.	≤ 0.18 diopters
Refractive power	≤ 0.125 diopters
Distortion	MIL-V-43511B
Optical correction	100%
Optical filters	
Laser	Classified
Flash	AR 70-71
Impact resistance	ANSI Z-87
Respiratory	
Resistance	
Inhalation	30 mm H_2O
Exhalation	15 mm H_2O
Flow rate	
Average	85 liters/minute
Inhalation	250 liters/minute
Exhalation	300 liters/minute

APPENDIX B: CHEMICAL BARRIER MATERIAL IDENTIFICATION AND TESTING: PREVIOUS STUDIES

The following is a summary of the material reports provided to Battelle by CRDEC.

A previous study¹ was conducted to identify potential materials for the following applications: elastomeric facepiece materials, flexible lens, rigid lens, rigid components, and hood barrier materials. Summaries of this information is presented below.

Elastomeric facepiece material candidates are silicone, natural rubber, neoprene, and fluorosilicone. Neoprene and Natural rubber are commonly used in industrial and military facepieces, but they are not recommended because of their problems with ozone attack, aging, toxicity, and not flexible enough in low temperature conditions. Silicone provides the best overall stability to environment conditions, but it has poor resistance to agent permeation. Fluorosilicones increased the resistance to agent permeation, but the physical properties, such as flexibility and resilience, were reduced.

Thin-film fluoropolymers (about 1 to 2 mils thick) can provide high resistance to chemical agent permeation. Attaching these fluoropolymer films to silicone as an outer barrier may be possible; however, attaching materials having vastly different modulus properties using adhesives has proven to be difficult. Some problems encountered are flex crazing and delamination, especially at low temperatures. It is not known if enough thickness of adhesive can be used to join low modulus silicone to higher modulus fluoropolymer films, but mechanical attachments might be used. Thermoplastic elastomer (TPE's) may be good agent barriers in the 25 to 30 mil thicknesses which might also be attached to silicone to form a laminated facepiece. Kraton® has been bonded to plasma and flame treated silicone and proprietary pressure sensitive adhesives have also been used with untreated silicone.

Materials for a flexible lens were investigated, but a flexible lens was not being pursued for use in the Lightweight Protective Mask (LPM) and the reader should refer to the study for this information.

Rigid lens materials include CR-39 and polycarbonate, both of which are commonly used in optical correction eye wear and provide impact resistance. One disadvantage of both these materials is that they have poor abrasion resistance which can be overcome with a suitable hardcoating. Polycarbonate was selected as the best candidate due to its light weight, high impact resistance and superior optical properties. Hardcoatings of interest for polycarbonate lenses are a super hard silicone coating by EYXENE and the epoxy-based coatings being investigated by the Air Force.

High impact plastics for making rigid components, such as check valve seats and voicemitter housings, are readily available for RES-O 21. Nylon are recommended for use, including:

- Glass-filled nylon 6/12 for POL and nuclear exposure
- Low grade nylon has shown good dimensional stability
- High grade nylons such as Zytel® and Minlon® are available for better moisture absorption resistance and thermal expansion

¹ "Memorandum for Record: Technology Survey Results (Materials)", Provided by Corey Grove, CRDEC

Thin-film chemical barrier materials were investigated for use as flexible hood. A number of materials are presented relative to their physical properties, including various types of fluorocarbon films. However, no chemical agent permeation data was presented and investigations of supported barrier films (i.e., thin barrier film laminated to a fabric substrate for strength and durability) were proposed.

Another material study² was completed which investigated various materials for use in the different applications of RESPO 21 protective masks. This study addressed the following applications:

- Hardcoating for polycarbonate lenses
- Coated fabrics for hoods
- Facepiece seal, suspension, and noseclip for "softshell" design
- Transparent facepieces

Chemical agent testing of HD and GB were performed for a large number of the materials identified; however, testing was generally stopped at 480 minutes. Therefore, it cannot be determined from the data whether the breakthrough of the agent would have occurred at 481 minutes or if it would not have occurred until 1440 minutes. (The design goal of the LPM is 24 hours which is 1440 minutes.)

The following materials, with the thickness specified in mils, provided at least 480 minutes of performance without chemical breakthrough for HD and GB:

- | | |
|---|--------------------------------|
| • Butyl rubber, 75 mil | • Hytrel 6350, 75 mil |
| • C-4 Polymer (Union Carbide), 75 mil | • Hytrel 5550, 75 mil |
| • Capron 77c | • Kel-F (Pencwalt), 75 mil |
| • Dow CPE, 75 mil | • Mobay urethane E-275, 75 mil |
| • EPDM (Du Pont), 75 mil | • Neoprene, 75 mil |
| • FEP-200, 5 mil | • Nylon and Saranex |
| • Fluorel, 75 mil | • Polyamide |
| • Gentex urethane, 75 mil | • Polysulfone, 75 mil |
| • Hardcoated polycarbonate, GE, 125 mil | • Saranex |
| • Hycar-1203, 75 mil | • Surlyn, 75 mil |
| • Hycar-4031, 75 mil | • Teflon |
| • Hypalon, 75 mil | • U.S.J EVA, 75 mil |
| • Hytrel 4055, 75 mil | |

- Note that Kalrez was not listed as tested

The following materials, bonded onto silicone slabs (75, 80, or 100 mils thick), provided at least 460 minutes (unless otherwise specified) without chemical breakthrough for HD and GB

- Parlene C, 1 mil
- Capran, 2 mil
- Saran, 1 mil
- Saranex, 4 mil
- Cellophane, 2 mil (400+)
- Kraton, 25 mil (420 HD, 460+ GB)
- Upjohn urethane(450+)

A material study³ consisting of testing materials which could provide 24 hour breakthrough times for HD was also completed. Sixty-three (63) materials were subjected to liquid HD challenge of 10 grams per square meter (g/m²). Of these materials, 12 had breakthrough times (vapor) exceeding 6 hours. The eight materials providing at least 20 hours of breakthrough time are:

- BL100 + 104L Latex B
- PIB + 104L Latex
- Ethyl-F
- Kalrez
- Barricade
- Tefguard
- Responder
- Chemrel Max

The latex blends were 50 percent blends by volume and consisted of butyl latex (BL100, Burke-Palmason Chemical Co.), polyisobutylene latex (PIB, Burke-Palmason Chemical Co.), and natural rubber latex (104L, Firestone). Kalrez® is a perfluoroelastomer by DuPont which provides many of the chemical properties of Teflon®, also produced by DuPont, but in an elastomeric form; however, the cost of Kalrez® is very high. The remaining materials listed above are very stiff and not suitable for a conforming hood design. Most of the testing included only one sample of each material for screening purposes. The thicknesses of the materials were not provided in the report.

Another report⁴ was provided by CRDEC studying flexible lens materials. This report was reviewed, but a summary was not presented here since a flexible lens design was not pursued for the LPM design.

The following tables were provided by CRDEC during the performance of this development task.

³ "MEMORANDUM for SMCCR-PPI, CRDEC: Agent Testing of RES-0 21 Materials" Leonard E. Nicholson, Maj, CS, Acting Chief, Eval Branch

⁴ Report on Flexible Lens Materials and Coatings, Written by MSA, Title Unknown, Provided by Corey Grove, CRDEC

Table 2
(Continued)
Individual Protection Flexible Lens &
Material Agent Resistance Estimates

Flexible Lens Materials

Materials	HD (min)	GD/GS(min)
Ethylene Acrylic (75 mils)	480+	480+
Urethane (Aliphatic) (75 mils)	1050	1440+
Urethane (Aromatic) (75 mils)	1440+	1440+
Silicone (100 mils)	85	160
Butyl (Conjugated Diene) (75 mils)	480+	480+
EPDM (75 mils)	480+	480+
Hydrin (75 mils)	480+	480+
Vinyl (75 mils)	---	---
Polyurethane (Pallathane) (25 mils)	210	480+
Polysulfide (75 mils)	480+	480+
Fluoroelastomers	---	---
-KEL-F (75 mils)	480+	480+
-Fluorel (75 mils)	480+	480+
-Viton (75 mils)	480+	1440+
-PNF (75 mils)	480+	1440+
TPE	---	---
-Solprene (75 mils)	480+	480+
-Kraton (25 mils)	420	460+
Chlorosulfinated Polyethylene (75 mils)	480+	480+

Values are estimates based on available data (see reference reports).

Mils = 1/1000 of an inch.

Table 3
(Continued)
Individual Protection Optical Coatings
(Flexible) : Agent Resistance Estimates

Optical Coatings (Flexible)

Materials	HD (min)	GD/GB (min)
Polyvinyl Fluoride (1 mil)	1440+	1440+
Polyvinyl Chloride (2 mil)	365	240
Ionomer (10 mil)	195	480+
Polyethylene Terephthalate (1 mil)	1440+	1440+
Polypropylene (3 mil)	57	---
Polyfluorohalocarbon (1.5 mil)	85	60
Polyvinylidene (1 mil)	460+	460+
Polyvinylidene Fluoride (1 mil)	460+	320
Nylon/Polyethylene	---	---
Fluoroelastomer (Fluorel, 2.5 mil)	450+	400
Polyamide (2 mil)	460+	460+
Chlorosulfonated Polyethylene (75 mil)	480+	---
Styrene/Butadiene (25 mil)	420	---
Parylene C (0.1 mil)	117	347

Mil = 1/1000 of an inch.

Table 3
Individual Protection Optical
Coatings (Flexible) Studies

Optical Coatings (Flexible)

Material	Trade Name	Urethane Bonding	Silicone Bonding
Polyvinyl Fluoride	Tedlar	Moderate Haze	Flex Crazing
Polyvinyl Chloride	VCF	Flex Cracking	---
Ionomer	Surlyn	Moderate Bonding	Flex Crazing
Polyethylene Terephthalate	Terphane Mylar	Poor Bonding, Flex Cracking	---
Polypropylene	B. Cor	Mod Bonding, Flex Cracking, Haze	---
Polyfluorohalocarbon	Aclar	Poor Bonding, Flex Cracking	---
Polyvinylidene	Saran	Darkens At High Temp. Poor Solvent	Flex Crazing
Polyvinylidene Fluoride	Fluorex Kynar	Mod Bonding, Flex Cracking	Flex Crazing
Nylon/Polyethylene	ST. Regis Film	High Haze, Mod Bonding	---
Fluoroelastomer	Teflon	---	Flex Crazing
Polyamide	Capran	---	Flex Crazing
Chlorosulfonated PE	Hypalon	---	---
Styrene/Butadiene	Kraton	---	No Crazing

Urethane Bonding = Ability to bond to urethane

Silicone Bonding = Ability to bond to silicone

Table 6
(Continued)
Individual Protection Flexible Barrier Film
Agent Resistance Estimates

Flexible Barrier Films

<u>Elastomer</u>	HD (min)	GD/GB (min)
Butyl (15 mils)	325	1200+
Neoprene (25 mils)	63	---
<u>Plastics</u>		
Polyethylene (10 mil)	60	---
Polypropylene (3 mil)	57	---
Polyvinyl Chloride (2 mil)	365	240
Polyvinyl Fluoride (1 mil) <i>TEFLON</i>	1440+	1440+
Polyvinylidene (1 mil) <i>ACCEL</i>	460+	460+
Polyvinylidene Chloride (2 mil) <i>SAVAN</i>	195	170
Polyvinylidene Fluoride (1 mil) <i>KYNAR</i>	460+	320
Polyamide (2 mil)	460+	460+
Chlorinated Polyethylene (10 mil)	60	---
Chlorosulfonated Polyethylene	---	---
Polyethylene Terephthalate (1 mil) <i>MYLAR</i>	1440+	1440+
Ionomer (10 mil)	195	480
<u>Fluoroelastomers</u>		
Viton (2.5 mil)	350	150
KEL-F	---	---
Ethyl F (27 mil)	>1220	---
Fluorel (2.5 mil)	450+	400

Table 6
(Continued)

<u>Fluoropolymers</u>	HD (min)	GD/GB (min)
PTFE (1 mil)	1440+	1440+
PFA (1 mil)	1440+	1440+
FEP (1 mil)	1440+	1440+
ETFE (1 mil)	1440+	1440+
ECTFE (1 mil)	1440+	1440+
PVF ₂ (1 mil)	1440+	1440+
CTFE (1 mil)	1440+	1440+
<u>Thermoplastic Elastomers</u>		
Polyolefin (10 mil)	76	---
Polyester (5 mil)	68	350
Polyether/amide	---	---
Styrene/Butadiene (5-10 mil)	115	420
Polyester Polyurethane	---	---
Polyether Polyurethane (10 mil)	99	---
<u>Latex</u>		
Acrylic (20 mil)	69	---
Natural Rubber (33 mil)	57	---
Butyl (32 mil)	>1220	---
Fluoroelastomer (30 mil)	121	---

Table 10
Industrial Suit Materials

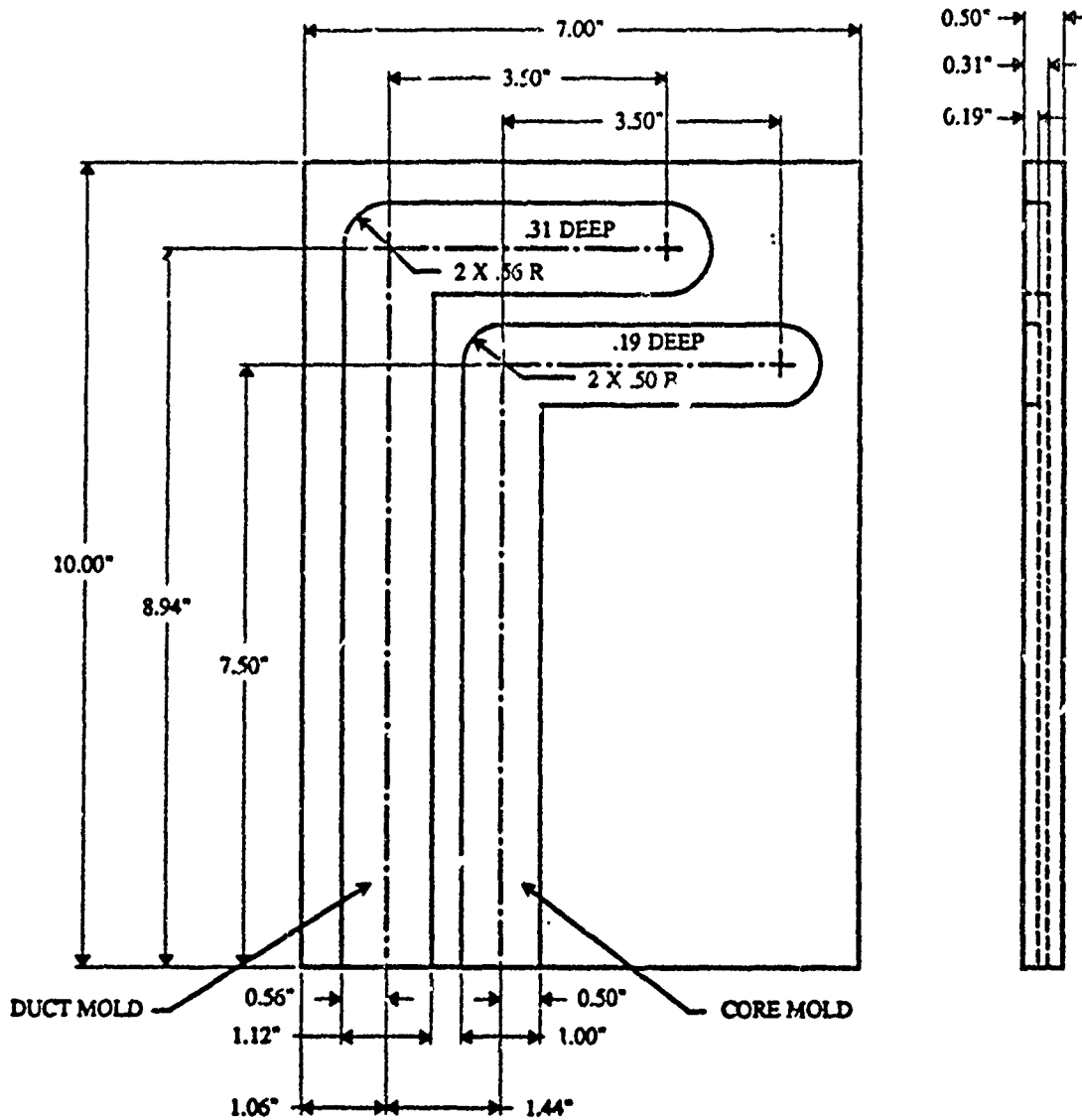
Material	HD	Summary
Neoprene (22 mil)	169	Too stiff for hood
V/N/C (14 mil)	167	" "
Barricade (16 mil)	>1220	" "
Tefguard (20 mil)	>1220	" "
Responder (15 mil)	>1220	" "
Challenger 5200 (11 mil)	432	" "
Chemrel-Max (12 mil)	>1220	" "
Repel	49	" "

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APPENDIX C: COMPONENT PART AND MOLD DRAWINGS

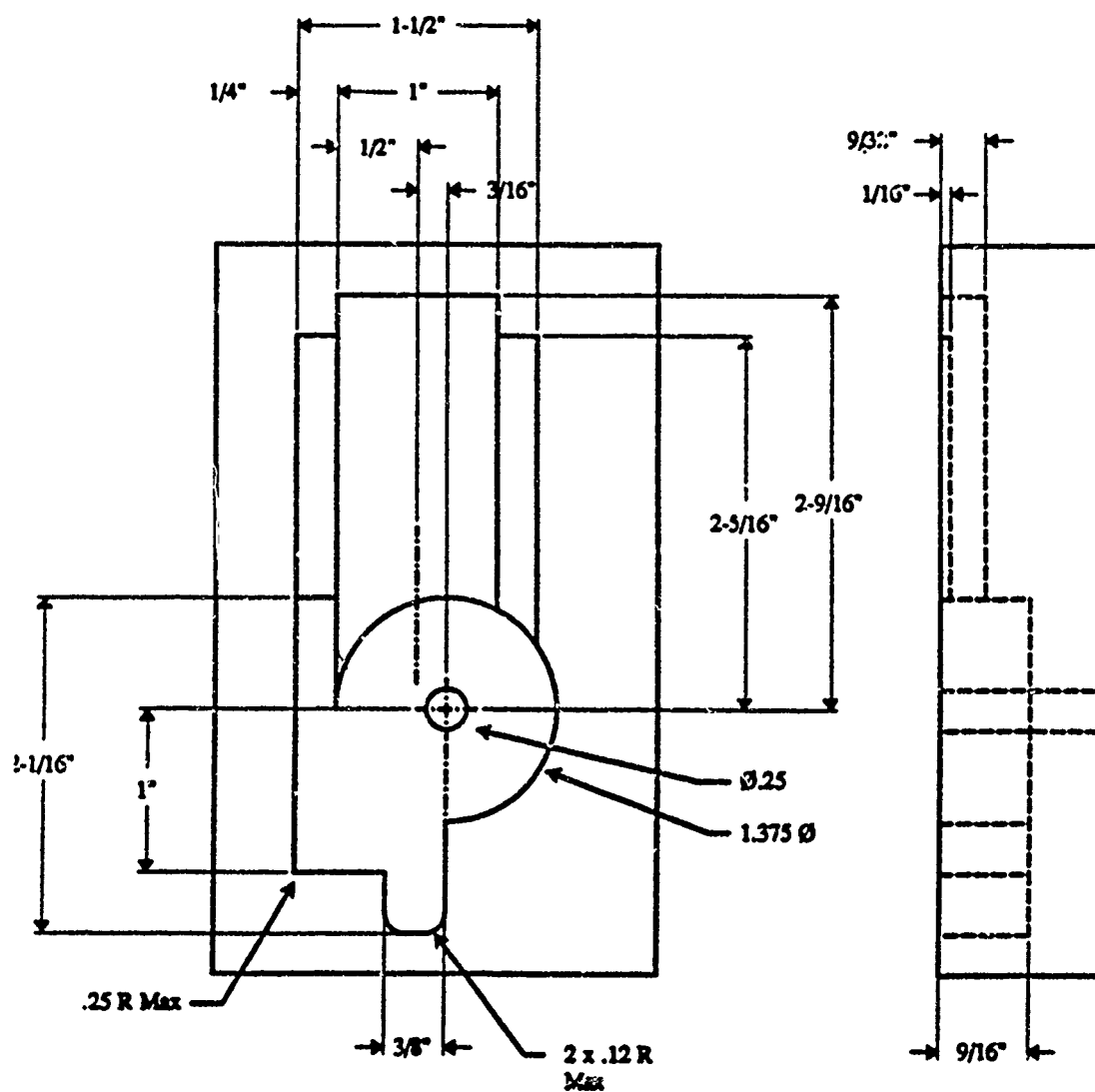
APPENDIX C: COMPONENT PART AND MOLD DRAWINGS

The following drawings provide the dimension used to machine the various components and the component molds used during LPM prototyping.

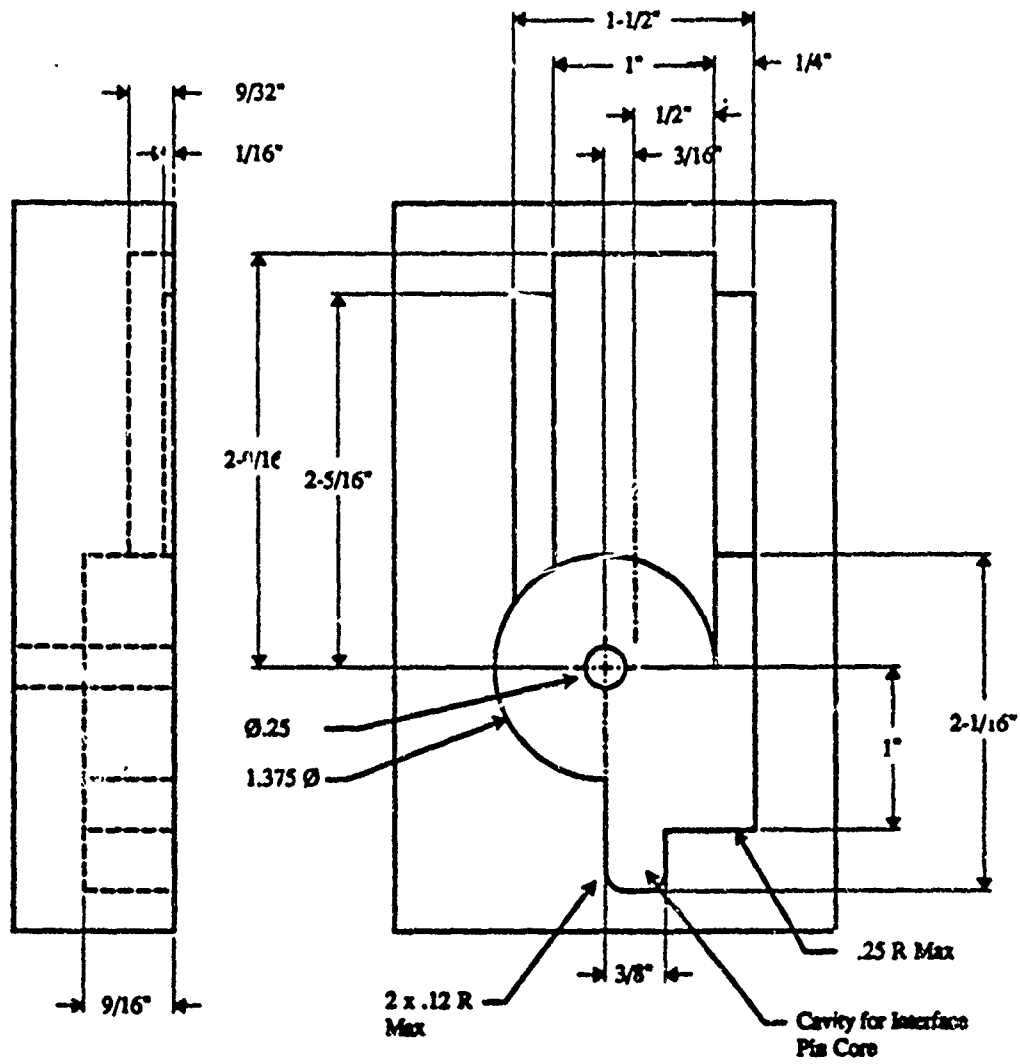


NOTE: ONE COVER PLATE IS ALSO REQUIRED
(7" X 10" X .25" THICK; ALUMINUM)

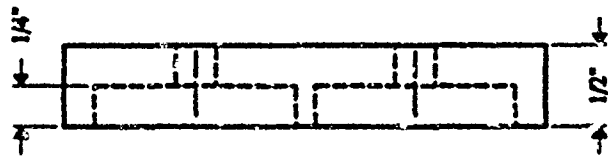
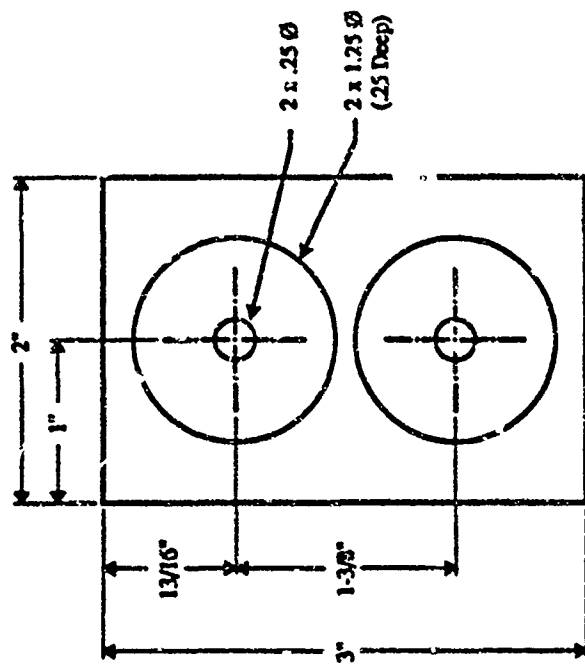
MOLD, AIR INLET & AIR INLET CORE
MATERIAL: ALUMINUM
SCALE: HALF
REQUIRED: ONE



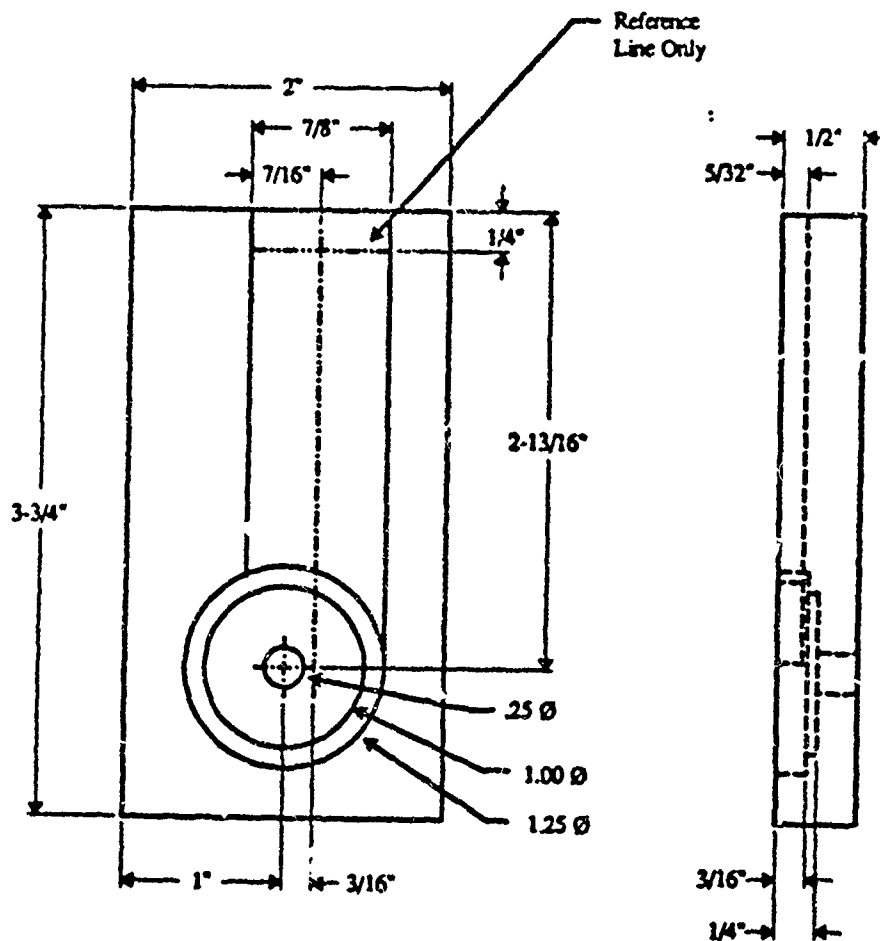
MOLD, RIGHT SIDE, CHECK VALVE ASSEMBLY
 MATERIAL: ALUMINUM
 SCALE: FULL
 REQUIRED: ONE



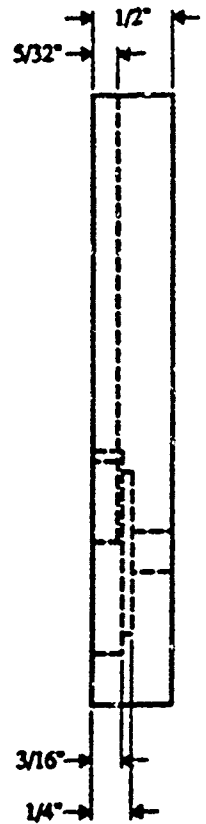
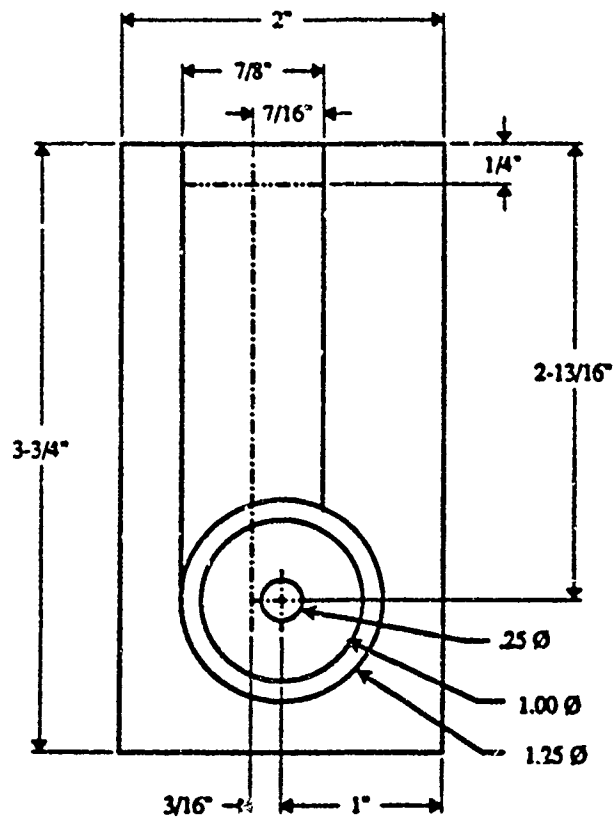
MOLD, RIGHT SIDE, CHECK VALVE ASSEMBLY
 MATERIAL: ALUMINUM
 SCALE: FULL
 REQUIRED: ONE



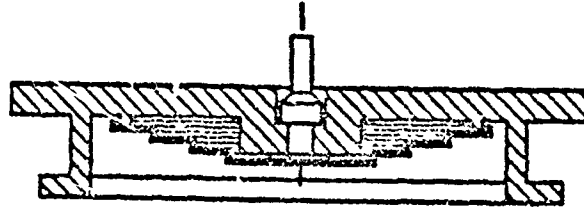
MOLD, CHECK VALVE
 MATERIAL: ALUMINUM 6061
 SCALE: FULL
 REQUIRED: ONE



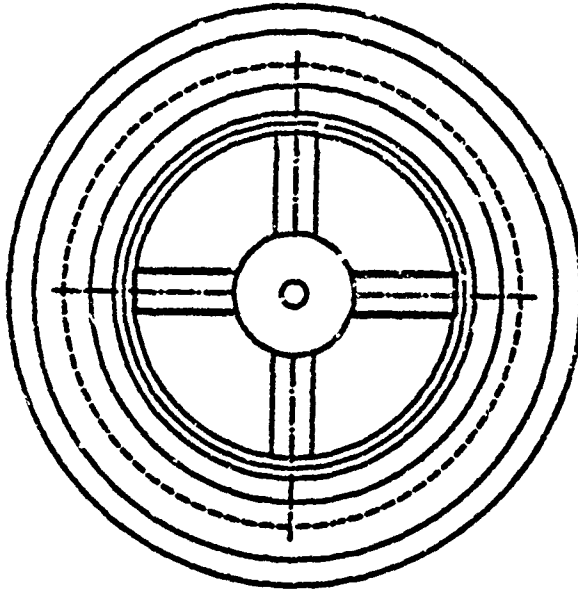
MOLD, DUCT, LEFT, CHECK VALVE ASSY
 MATERIAL: ALUMINUM
 SCALE: FULL
 REQUIRED: ONE



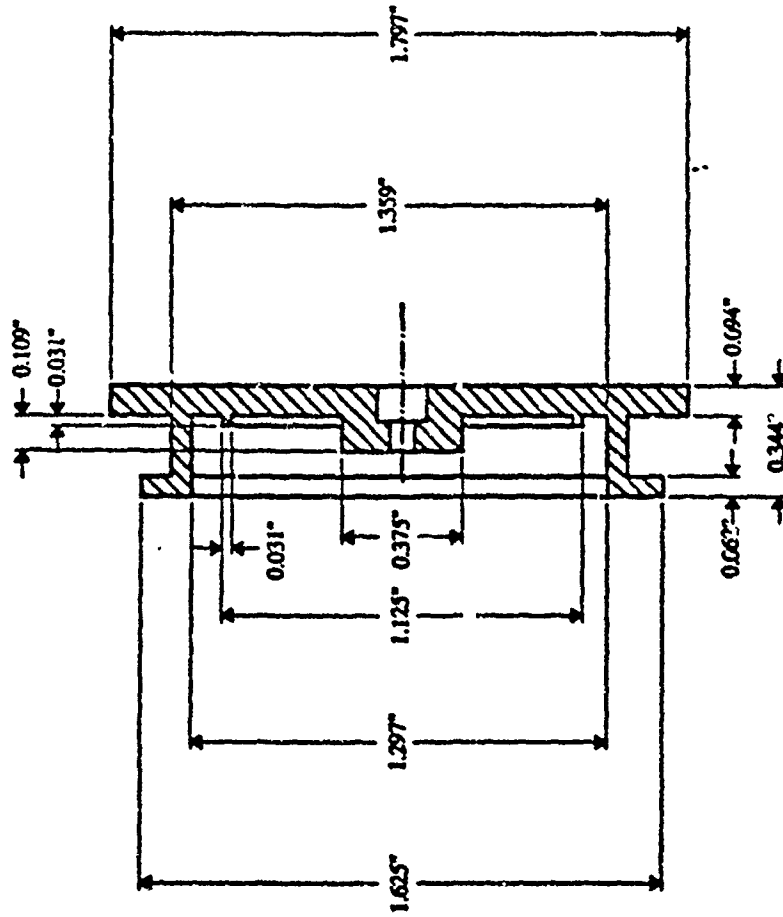
MOLD, DUCT, RIGHT, CHECK VALVE ASSY
 MATERIAL: ALUMINUM
 SCALE: FULL
 REQUIRED: ONE



2X Scale

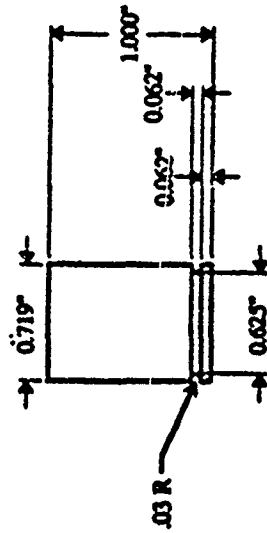


CONCENTRIC CHECK VALVE SEAT WITH PIN ATTACHMENT
Sheet 1/2

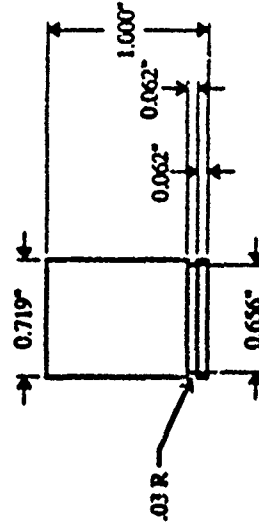


2X Scale

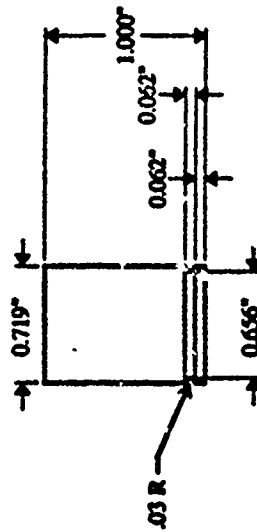
CONCENTRIC CHECK VALVE SEAT WITH PIN ATTACHMENT
Sheet 2/2



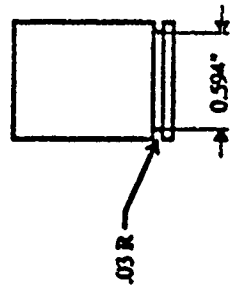
Filter Connector -
Female Mold, Core, Large Detent
Material: Aluminum
Scale: Full
Quantity: One



Filter Connector -
Female Mold, Core, Small Detent
Material: Aluminum
Scale: Full
Quantity: One



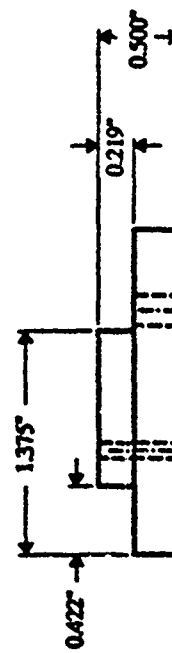
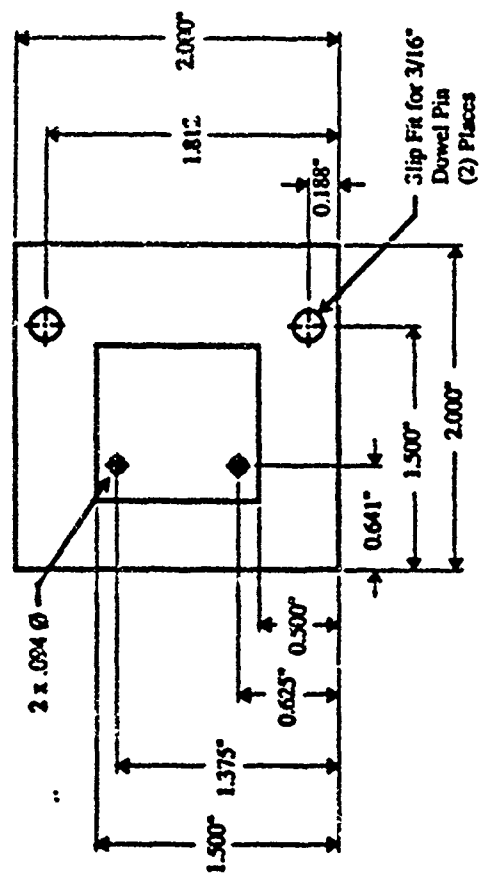
Existing Design



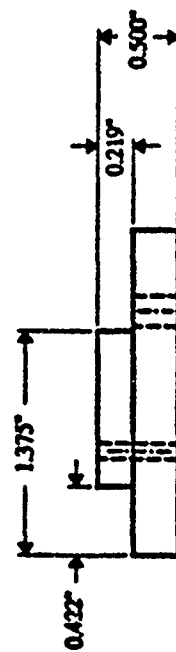
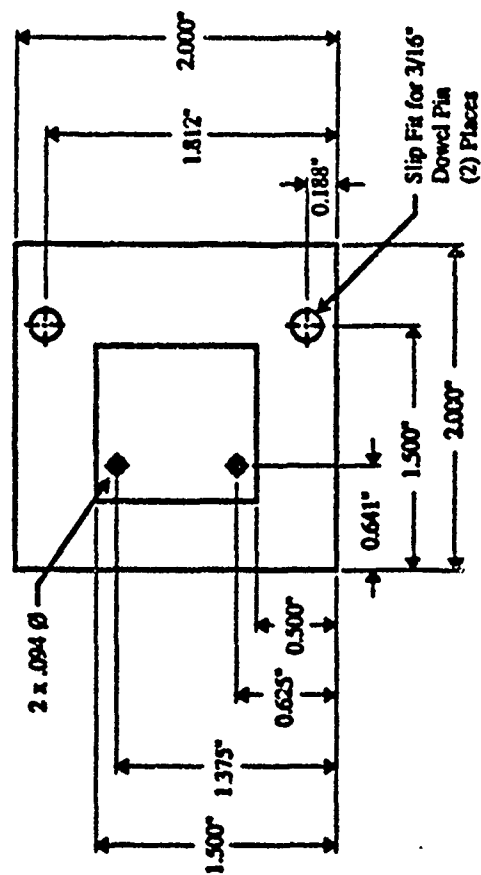
Modified Design

MODIFY EXISTING PART

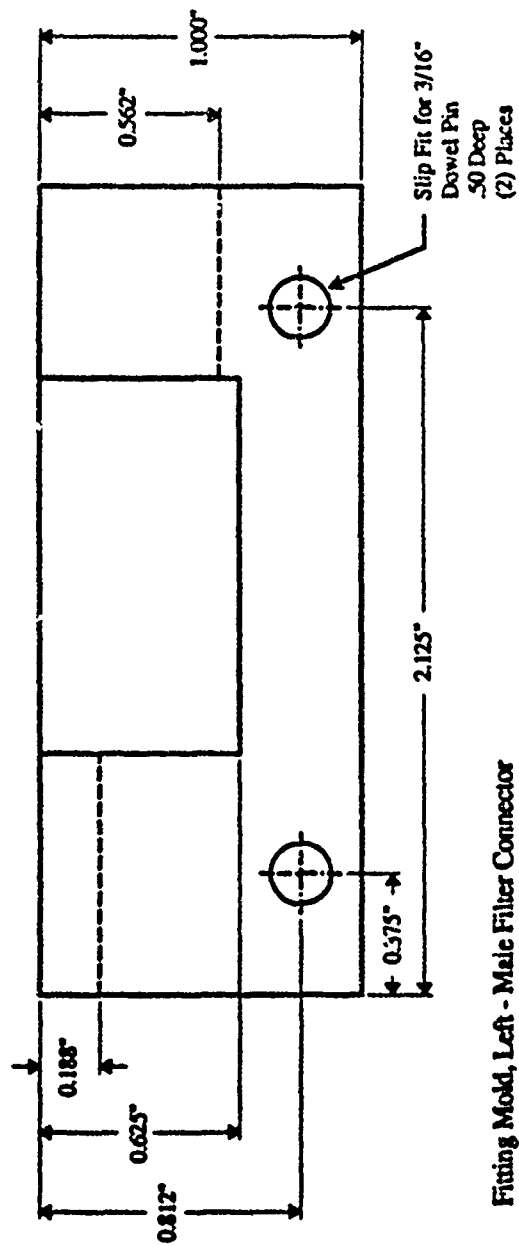
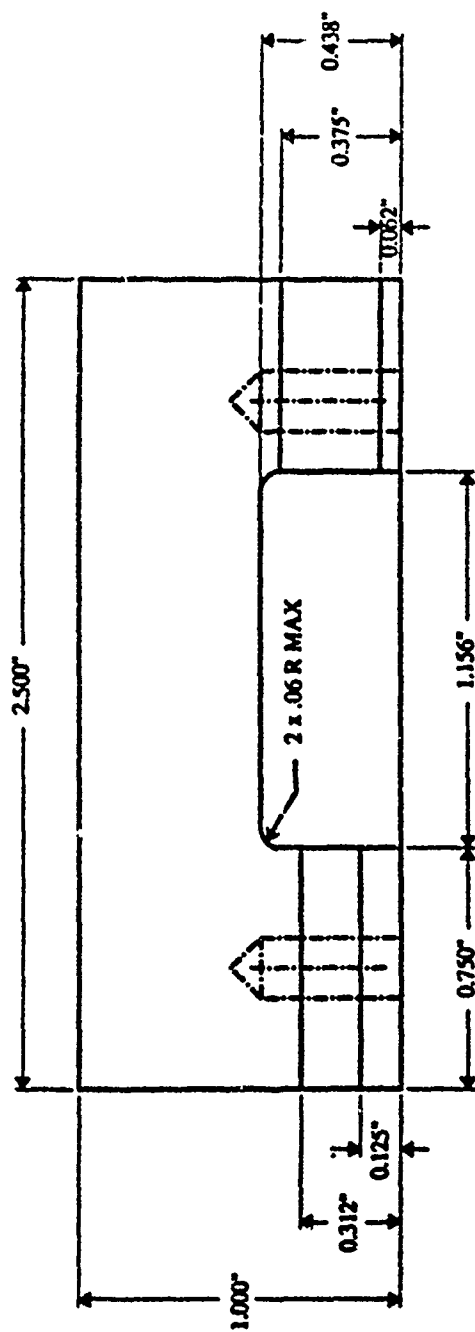
Filter Connector -
 Female Mold, Core, Small Detent
 Material: Aluminum
 Scale: Full
 Quantity: One



**Filter Connector -
Female Mold, Bottom
Material: Aluminum
Scale: Full
Quantity: One**



Filter Connector -
Female Mold, Bottom
Material: Aluminum

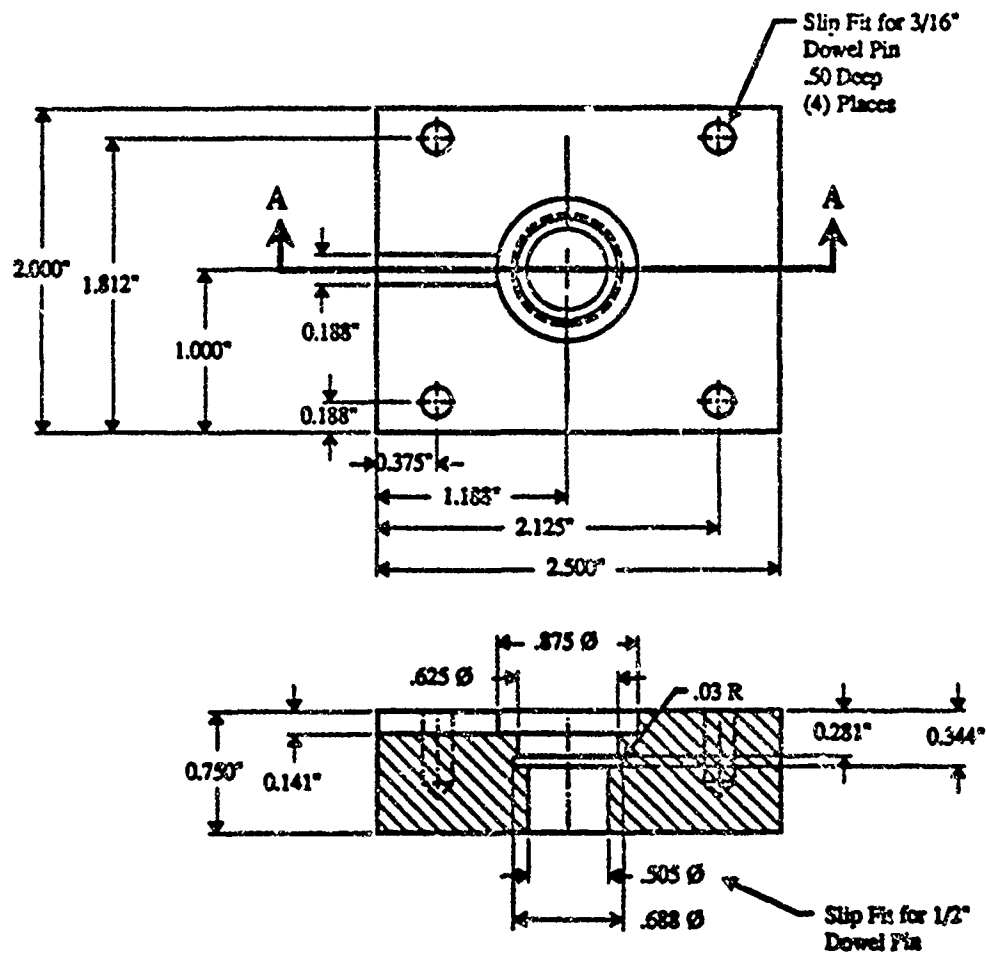


Fitting Mold, Left - Male Filter Connector

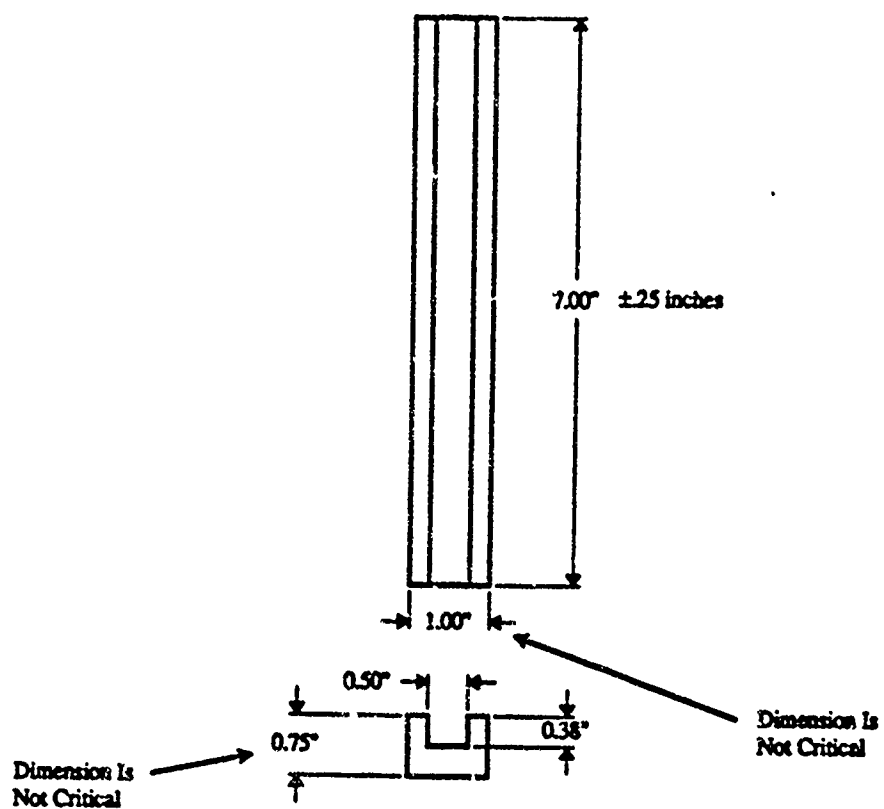
Material: Aluminum 6061

Scale: 2X

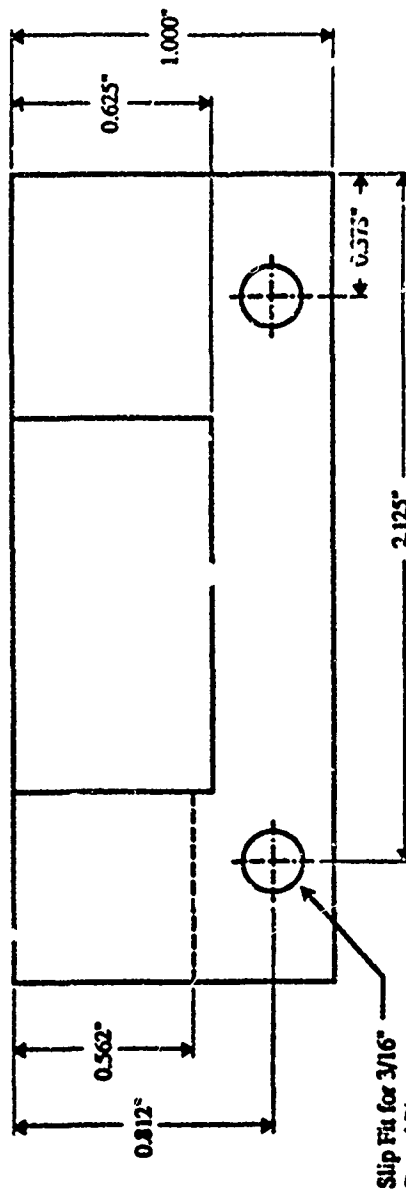
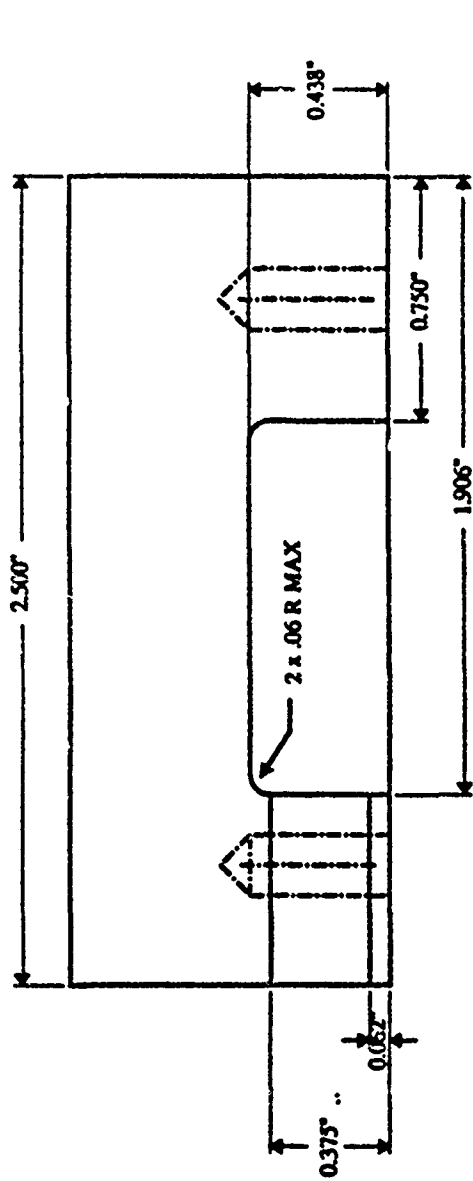
Quantity: One



Fitting, Mold, Bottom - Male Filter Connector
 Material: Aluminum 6061
 Scale: Full
 Quantity: One

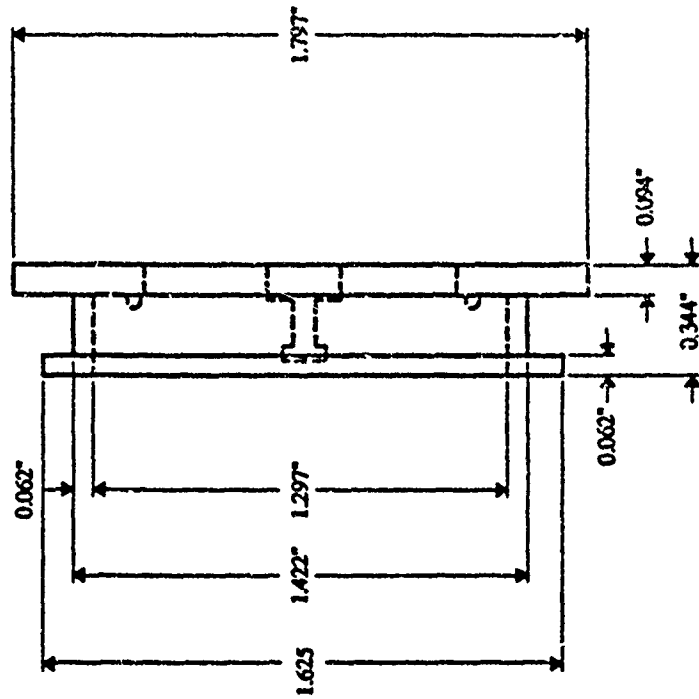
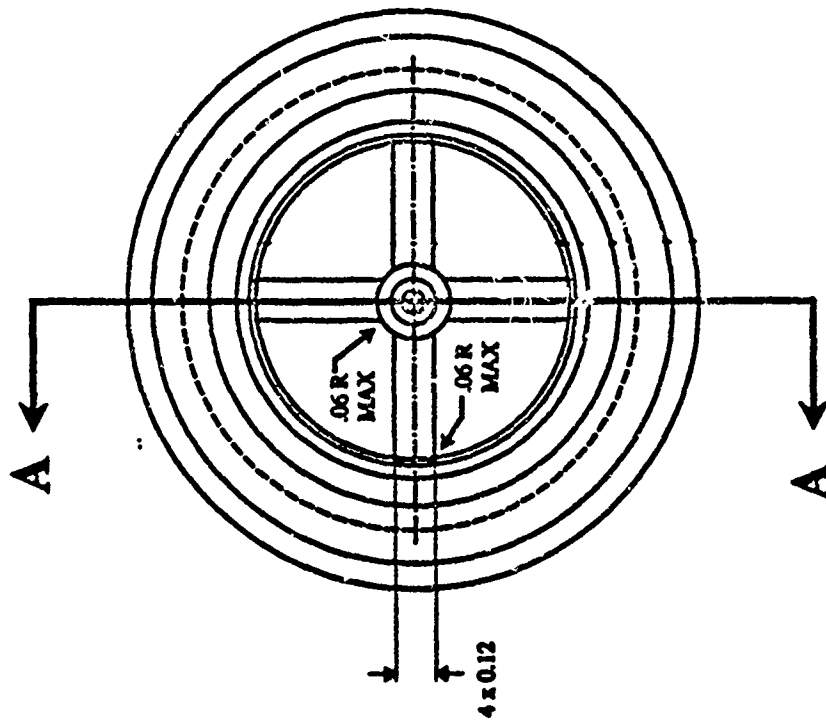


CHIN SEAL MOLD
MATERIAL: ALUMINUM
SCALE: HALF
REQUIRED: ONE



Slip Fit for 3/16"
Dowel Pin
.50 Deep
(2) Places

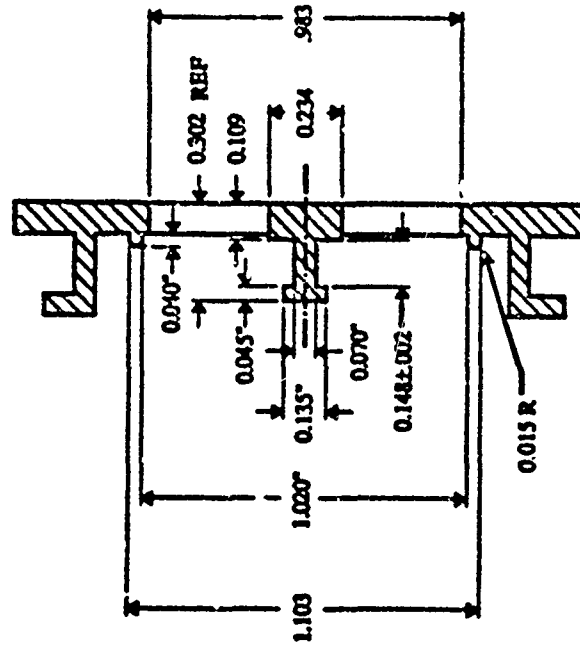
Fitting, Mold, Right - Male Filter Connector
Material: Aluminum 6061
Scale: 2X
Quantity: One



2X Scale

CONCENTRIC CHECK VALVE SEAT WITH POST ATTACHMENT
Sheet 1/2

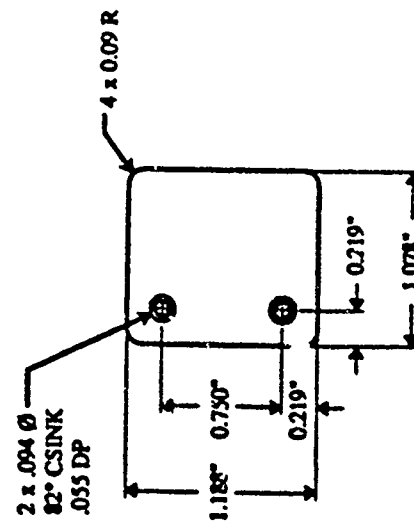
Break All Edges 0.005
Unless Otherwise Specified



Scale

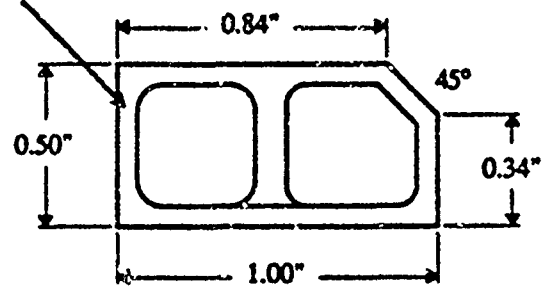
Section A-A

CONCENTRIC CHECK VALVE SEAT WITH POST ATTACHMENT
Sheet 2/2



BOTTOM PLATE - CONNECTOR, FILTER
 MATERIAL: ALUMINUM
 SCALE: FULL
 QTY: FOUR

0.06 Width Typical



1/8 inch
minimum
thickness

Radius of back Surface
is 1.8 inches

Reduced Size Rectangular Check Valve Seat

D-1

APPENDIX D: MATERIAL LIST AND SPECIFICATIONS

APPENDIX D: MATERIAL VENDOR REFERENCE

The following is a list of the materials and their vendors which were used during the fabrication of the LPM mockups and prototypes. Also included is the list of adhesives identified in a search along with the testing of adhesives obtained.

- | | | |
|---|---|---|
| 1 | Master Mend™ Epoxy
Duro™ QM-60
Loctite Corporation | A two-part epoxy adhesive having a 90-minute cure time at room temperature. |
| 2 | Master Mend™ Epoxy
Duro™ TM-51
Loctite Corporation | A two-part epoxy adhesive having a 5-minute cure time at room temperature. |
| 3 | Acryloid
B-67MT
Rohm and Haas
Philadelphia, PA | An acrylic casting resin. System would not completely cure in a Sylgard ® 182 silicone mold. |
| 4 | Polyester Fiberglass Resin
Dynatron/Bondo Corp.
Atlanta, GA | Fiberglass resin commonly used in auto body repair work. Cured parts of only resin are very brittle and not very strong. |
| 5 | Acrylic urethane
Battelle
Columbus, OH | A UV curing polymer consisting of various percentages of polymer, diacrylate, and triacrylate, and UV-curing catalyst (See below) |
| 6 | Acrylated epoxy
Battelle
Columbus, OH | A UV curing polymer consisting of various percentages of polymer, diacrylate, and triacrylate, and UV-curing catalyst (See below). |
| 7 | Polyurethane TC 960
60 Shore Hardness A
BJB Enterprises
Garden Grove, CA | This two-part urethane has a pot life of about 25 minutes and a room-temperature cure time of about 8 hours. This cure time can be significantly reduced by heating the poured mold at about 110° F. This yellowish rubber is translucent. |
| 8 | Polyurethane TC 960-B
60 Shore Hardness A
BJB Enterprises
Garden Grove, CA | This two-part urethane is the same as the TC 960 castable urethane, except that it is a brush-grade. The mixed viscosity was too high for degassing in the mixing pot. The pot life is about 25 minutes and it has a room-temperature cure time of about 8 hours. This yellowish rubber is translucent. |

- | | | |
|----|--|---|
| 9 | Polyurethane TC 274
Pour-In-Place Foam
BJB Enterprises
Garden Grove, CA | This two-part urethane foam has a mixing and pouring time of about 90 seconds before it violently foams. It is an open-cell foam which provides some skinning depending upon the age of material and venting of the mold. The foam is white at first with yellowing occurring with age. |
| 10 | Polyurethane TC 2510 Epoxy
BJB Enterprises
Garden Grove, CA | This two-part epoxy system is a transparent polymer which has a pot life of about 25 minutes and a room-temperature cure time of several hours |
| 11 | Chevot Clay
BJB Enterprises
Garden Grove, CA | Clay/wax composition stiff for sculpting details while it can be melted at about 200°F for shaping or pouring. |
| 12 | Epoxy Parfilm
Price-Driscoll Corp.
Farmingdale, NY | Film forming release for epoxy systems. |
| 13 | Sylgard 182
Silicone Rubber
Dow Corning | This two-part silicone system is heat-cured with a cure time of 4 hours at 150° F. It has a low viscosity prior to curing and has an 8 hour pot life. It is a transparent material which does not readily bond to other materials. |
| 14 | Sylgard 184
Silicone Rubber
Dow Corning | This two-part silicone system is room temperature cured with a cure time of 24 hours. It has a low viscosity prior to curing and has a 2 hour pot life. It is a transparent material which does not readily bond to other materials. |
| 15 | Sylgard 186
Silicone Rubber
Dow Corning | This two-part silicone system is room temperature cured with a cure time of 24 hours. It has a relatively high viscosity prior to curing and has a 2 hour pot life. The air bubbles could not be removed with a vacuum due to higher viscosity. It is a transparent material. |
| 16 | HS II RTV
Silicone Rubber
Dow Corning | This two-part silicone system is heat-cured with a cure time of 24 hours. It has a relatively low viscosity prior to curing and has a 2 hour pot life. The cured material is opaque white and can bond to other materials. |
| 17 | Algi-Cast
M465 Molding Compound
Tri-ess Sciences, Inc.
Burbank, CA | Fast setting molding compound made from organic materials which breaks down over time; therefore, only used for temporary molding. |

18	Hydrostone U.S. Gypsum Products Industrial Gypsum Division Chicago, IL	
19	Ultracal 30 U.S. Gypsum Products Industrial Gypsum Division Chicago, IL	
20	High Temperature Casting Resin FR-44- Gray w/ Catalyst 5413-C Fiber Resin Corporation Burbank, CA	Metal-Filled Epoxy
21	Olefin Spacer Fabric Stock no. 2006-027-1 Pittsfield Weaving Co. New Hampshire	Loose woven olefin spacer material having a width of 74 to 76 inches. Available most of the time.
22	Saran Spacer Fabric Stock no. 9006-009-1 Pittsfield Weaving Co. New Hampshire	Woven Saran spacer material having a width of about 54 inches. Not a loose weave for low pressure drops during air flow conditions.
23	B/LPS Lens System American Optical Corporation Southbridge, MA	Ballistic protection eyewear system including translucent glasses, bronze colored glasses, and a laser outsert.
24	Kalrez DuPont	An elastomeric PTFE material having the polymeric code of FFKM. This material is ultra-expensive.
25	Flexane Brushable Urethane ITW Devcon Danvers, MA	Material is black in color. Can combine with curing accelerators and flexing agent, Flex-Add, also produced by ITW Devcon
26	Flex-Add Flexing Agent ITW Devcon Danvers, MA	
27	Fluoroglide Parting Compound Performance Plastics Wayne, NJ	Fluoropolymer dry film lubricant, film-bonding grade and anti-sticking agent.
28	Silicone Parting Spray No. S512 C. Griffin Falls, OH	Mold release agent, colorless, odorless, and clean
29	3-6548 Silicone RTV Dow Corning	Two-part silicone foam which has a mixing and pouring time of about 1 minute. It is black in color and doesn't have good strength or tear resistance.

- | | | |
|----|---|--|
| 30 | RTF 762 Silicone Rubber Foam
General Electric Company
Silicone Products Div.
RTV Products Dept.
Waterford, NY | Two-part silicone foam which has a mixing and pouring time up to 14 minutes. It is white in color and has good strength. |
| 31 | Wonderbond
Elmer's®
Borden, Inc. | Cyanoacrylate adhesive similar to "SuperGlue" |
| 32 | Butyl Latex BL-100
Burke-Palmason Chemical Co.
Pompano Beach, FL | |
| 33 | TN Latex
Ausimont USA, Inc.
Morristown, NJ | Fluoropolymer latex |
| 34 | Natural Rubber Latex 104L
General Latex & Chemical Corp. | |
| 35 | Darlington Fabrics Corp.
Westerly, RI | |

The acrylic urethane compounded by Battelle was based on PurElaSt 186 (PES 186) polymer from Polymer Systems Corporation. The diacrylate used was 1,6 HDODA. The triacrylate was Photomer 4149. The catalyst was a 2 percent Irgacure 651 from Ciba Geigy.

Formulation No.	Polymer PES 186	Diacrylate 1,6 HDODA	Triacrylate Photomer 4149
1	25	70	5
2	70	25	5
3	70	5	25

The acrylated epoxy compounded by Battelle was based on Photomer 3016 polymer from Henkel. The diacrylate used was 1,6 HDODA. The triacrylate was Photomer 4149. The catalyst was a 2 percent Irgacure 651 from Ciba Geigy.

Formulation No.	Polymer Photomer 3016	Diacrylate 1,6 HDODA	Triacrylate Photomer 4149
1	25	70	5
2	70	25	5
3	70	5	25

A search was made of various types of adhesives which could be used in the assembly of the LPM prototypes. Following this list of adhesives are the adhesive testing which

was performed to evaluate bonding the different hood materials to both chemically etched FEP facepiece material and to cast urthane (used in the air management components).

Nylon

Resorcinol-formaldehyde
Phenol-formaldehyde • resorcinol formaldehyde
Epoxy-polyaminoamide
Carboxylic acrylic
Polyamide
Nitrile-phenolic
Nitrile rubber cement
Polyurethane rubber cement

Film Adhesives

Norwood Industries, Pennsylvania (215) 647-3500
Phenolic film adhesive -- Plymaster PM220
Urethane film adhesive -- Plymaster PM253
No cure schedules

BF Goodrich, Ohio (216) 374-2900
Nitrile-phenolic film adhesive -- Plastilock 601
May require too high a temperature to cure (1 hr @ 350 F 100 psi)

GFF, Cincinnati, Ohio (800) 582-1502
Polyamide film adhesive -- Fus-O-Bond N-OO
No cure schedule

Dielectric Poly, Massachusetts (413) 432-3288
Nitrile phenolic film adhesive -- Neltape NT-601
Polyamide film adhesive -- Neltape NT-381
No cure schedule

Allied Resin Corporation, New Jersey (201) 455-5010
Polyamide film adhesive -- Capran 77C
No cure schedule

American Cyanamid, Maryland (301) 939-1910
Michigan (313) 353-9180
Unsupported epoxy film adhesive -- Cybond FM-1000
Too high cure schedule? (1 hr 350 F 40 psi)

2-Part R.T. Cure Adhesives

American Cyanamid, Maryland (301) 939-1910
Epoxy — Cybond 1112
Cure (2 hrs @ 77 F)

Ciba-Geigy, New York (914) 347-4700
Arathane Ay 5500 + HV 5501 or HV 5511
(Polyurethane 20 min pot-life or 5 min pot-life)
(1 day @ 68 F or 8 hrs @ 68 F)

Conap, Incorporated, New York (716) 372-9650
Polyurethane for plastic — Conathane DPAD-11877
They have dozens of urethane adhesives (cure 2 days at 77 F, 37 min pot-life)

Hot-Melt Adhesives

H.B. Fuller Company, MN (612) 481-1816
Polyamide — HM 1504 (S.P. 292 F)
Polyamide — 816

National Starch, New Jersey (908) 695-5000
Polyurethane — Duro-Flex 72-9014

Type of Adhesive	Vinyl	Teflon	Fabric	Comments
Weldwood Contact Cement	fail	fail		Glue adhered to vinyl and teflon
3M Super 77	fail	fail	fail	Glue adhered to polyurethane
Duco Cement	fail	fail	fail	Glue adhered to polyurethane
Borden Wonderbond	held	held	fail	Both films fail after pulling hard
Seal All	fail	fail	fail	Glue adhered to vinyl and not to teflon
Duro Master Mend Epoxy	fail	fail	fail	Glue adhered to vinyl and teflon
Dow Corning Silicone Sealant	fail	fail	held	Glue adhered to vinyl and teflon
BJB TC-960 A/B Polyurethane	held	held	fail	Both materials fail after pulling hard
Scotchweld 2216 E/A Epoxy Adhesive	fail	fail	fail	Glue adhered to vinyl, teflon and fabric
Scotch Grip 847	held	held	fail	Able to pull off but very hard
HB Fuller Hot Melt HM1504	fail	fail	fail	Glue adhered to vinyl and teflon
Ciba Geigy XMH 8520 Polyurethane	held	held	fail	Held films fast
HB Fuller UR 2139A Polyurethane	held	held	fail	Held vinyl better than teflon
Aquaseal Seam Seal			fail	Did not test other films

E-1

APPENDIX E: LENS THERMOFORMING

APPENDIX E: LENS THERMOFORMING

A lens design was established based on guidelines found in the literature. This lens was flat in the vertical meridian which basically forms a two-dimensional lens. The following is a discussion of the procedures used to thermoform lenses using 0.12-inch thick polycarbonate (Lexan by General Electric).

An aluminum mold was then machined based on the horizontal curvature of the lens design. This mold formed the inside surface of the lens (i.e., male mold) where the polycarbonate was heated and wrapped around the mold. A sheet of polycarbonate was cut to size and clamped to the peak of the aluminum mold. Before the polycarbonate was heated, the sheet was flat. As it was heated to about its melting point, the polycarbonate would wrap about the mold because of its loss of strength. Once the sheet was fully conformed to the mold surface, it was removed and allowed to cool, thus resulting in a lens plaque. A line was then scratched into the polycarbonate along the bottom surface of the mold to form a reference line. Flat patterns of the lenses were then cut from paper and glued to the lens plaque. The lenses were cut out from the plaque and the edges ground flat. The pattern glued to the polycarbonate was easily cleaned off with soap and water.

Initially, the thermoforming temperature was not known and was found by trial and error. In the first thermoforming attempt, the polycarbonate was slowly heated until it began to soften and fall about the mold. The final temperature was about 330°F. However, some stiffness was still present in the polycarbonate sheet and the sheet was pushed against the mold.

The second thermoforming attempt was made at a higher temperature, 355°F, to eliminate the stiffness in the sheet. However, at this temperature, small air bubbles formed inside the polycarbonate at the areas of sharpest curvature.

In the third thermoforming attempt, hose clamps were used to force the polycarbonate against the mold and held there until the polycarbonate was cooled. A thin Teflon® FEP film and a thin sheet metal cover were placed between the hose clamps and the polycarbonate to better distribute the hose pressure. (Permanent marks were left on the polycarbonate where the C-clamps used to hold the polycarbonate to the mold were clamped.) The hose clamps basically formed an inexpensive female mold. This mold assembly was heated to about 340°F. The assembly was periodically removed from the oven and the hose clamps tightened during the heating process. After heating, the assembly was completely cooled and then disassembled. Some air bubbles were formed in the polycarbonate. Also, stress marks were left in the polycarbonate from the hose clamps. These stress marks generally could not be seen except under certain lighting conditions. Lenses were cut out from this lens plaque from the areas which did not contain these defects.

To get the best lenses, it is recommended that a female mold be made so that the male and female mold together will force the polycarbonate to the desired shape. The polycarbonate should only be heated to about 330° to 340°F to preclude the formation of air bubbles inside the polycarbonate.

F-1

APPENDIX F: DIP-COATING PROCEDURES

APPENDIX F: DIP-COATING PROCEDURES

Dip-coat testing to produce an LFM prototype was initiated by forming simple dip-coating on glass test tubes and on glass test tubes lined with a nylon/Lycra® fabric. The fabric substrate was sewn together to form a sleeve which was stretched about 20 percent as it was placed on the test tube. The latexes used were the butyl latex BL-100¹ and the natural rubber latex 1-N-861, clear² previously determined to provide a good chemical agent permeation barrier for HD.³ However, the natural rubber latex used in this previous testing program was 104L produced by Firestone.⁴ The 104L was not available for purchase at the time of testing, thus explaining this substitution.

The natural rubber latex was already compounded when it was obtained. The butyl latex did need to be compounded. Instructions of different compounding methods were suggested and the following compounding was performed.

<u>Compound</u>	<u>Parts by Weight</u>
Butyl latex BL-100	160
Zinc oxide (50% slurry) ⁵	8.3
Sulfur (50% slurry) ⁵	4.4
Butyl zincate (50% slurry) ⁵	8.0
Setsit 5 (as received) ⁵	5.0

The two latexes were mixed together evenly by weight and the mixture strained through cheesecloth to remove any particulate matter. A solution of 50 percent nitrate coagulant was used. The test tube was slowly dipped in the latex and slowly pulled back out. The test tube was then slow dipped in the coagulant and slow pulled back out. This process was repeated until

1 BL-100 butyl latex by Burke-Palmason, Panama Beach, FL

2 1-N-861 (clear) natural rubber latex by General Latex and Chemical Co.

3 "MEMORANDUM for SMOOR-PPI, CRDEC: Agent Testing of RESPO 21 Materials" Leonard E. Nicholson, Maj, CS, Acting Chief, Eval Branch

4 Katz, Harry S. and Radha Agarwal, Utility Development Corp. Identify, Evaluate and Recommend Materials for Use in the Next Generation of Respiratory Protection (RESPO 21) Oct 31, 1990

5 R.T. Vanderbilt Co.

the desired thickness of the dip coat was attained. The test tube was then suspended in distilled water overnight to leach out excess calcium nitrate. However, problems were encountered because the coagulant seemed ineffective for the latex solution. As the sample was suspended in the distilled water, the latex came off of the test tube and a sample could not be formed. Alcohol was added to the calcium nitrate coagulate to sensitize the butyl latex as suggested in the compounding instructions; however, this was not successful.

The supplier of the butyl latex was contacted for suggestions. The supplier did not have any suggestions for a working coagulant and offered to send a sample of developmental butyl latex, BCL-200, which will work with common coagulants (i.e., calcium nitrate solution).

The BCL-200 latex was compounded using the same procedures and chemicals as the BL-100 compounding. This new butyl latex was then mixed with the natural rubber latex and filtered through cheesecloth. Dip-coating test tubes in this latex still was not successful. The coagulant seemed to "shock" the latex which prevented a smooth dip coat to be attained. The amount of latex "sticking" to the test tube per dip was also very small so that a very large number of dips would have been necessary.

To decrease the shocking effect of the coagulant, the percent of calcium nitrate was reduced to 25 percent (75 percent distilled water). This seemed to improve the dipping process somewhat, although the coating per dip was still very thin. It was found that by letting the test tube sit in the latex for about 30 minutes and then letting the latex air dry after each dip for about 30 minutes before dipping in the coagulant kept the latex from leaching off of the test tube. This method was used as the final procedures. A number of coats were applied so that the overall thickness was about 0.06 inches. The dip-coat sample was then suspended in distilled water overnight to leach the coagulant. The sample was then suspended in 160°F water for three hours followed by one half hour in boiling water to complete the cure (the butyl latex compounding instructions suggested curing in high humidity conditions). This sample was very smooth and looked good; however, the tensile strength was very low and the sample was easily torn. Because this procedure resulted in a unusable sample and a major effort would have been required to develop a satisfactory process, the dip-coating testing was discontinued.